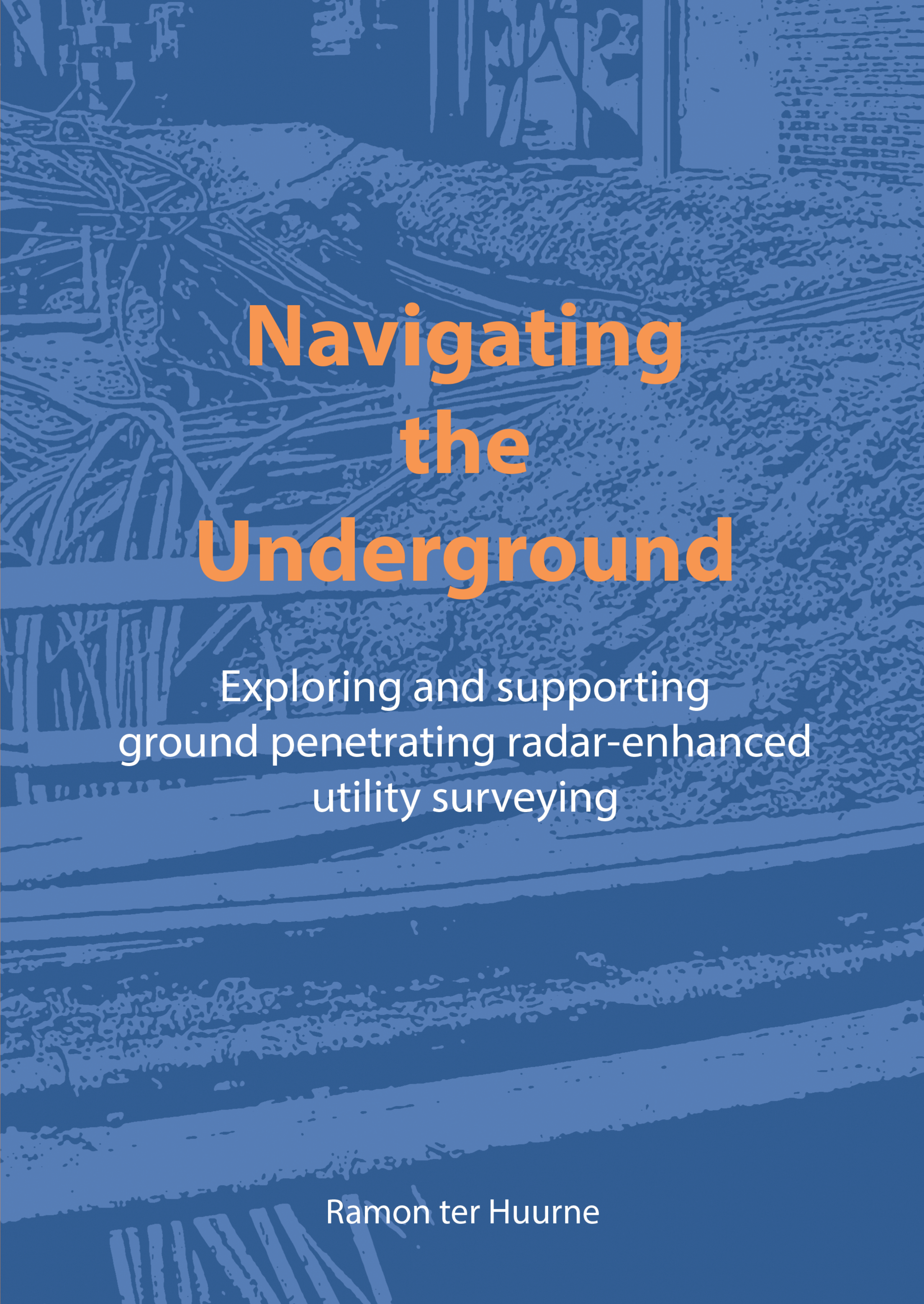

Navigating the Underground

Exploring and supporting ground penetrating radar-enhanced utility surveying

Ramon ter Huurne

NAVIGATING THE UNDERGROUND

EXPLORING AND SUPPORTING GROUND PENETRATING RADAR-ENHANCED UTILITY SURVEYING

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DISSERTATION

to obtain
the degree of doctor at the University of Twente,
on the authority of the rector magnificus,
prof.dr.ir. A. Veldkamp,
on account of the decision of the Doctorate Board
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by

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Prologue

Sitting in the back of my parents' car, I vividly remember passing grand infrastructures on our way to many European holiday destinations. The Europa Bridge and the Gotthard Tunnel particularly stand out in my memory. These impressive structures fascinated me and inspired my later decision to study civil engineering. At the time, I never imagined that I would eventually pursue a PhD focusing on a type of infrastructure just as grand but far less visible: underground utilities.

My perspective shifted in 2016 when I inquired about PhD opportunities with Professor André Dorée. Initially, options were limited. However, André offered me an alternative a few months later: an Engineering Doctorate. I accepted, and during this trajectory, I developed an ontology to digitally model utilities, deepening my fascination with this hidden infrastructure. I came to see cables and pipelines, invisible for the most part, as a type of infrastructure that forms the lifeblood of our modern world, akin to veins in the human body. They transport the essential resources that our society relies on. When they function correctly, society runs smoothly. However, significant disruptions occur when they are damaged or broken, much like how clogged or burst veins can threaten our lives.

This analogy underscores the importance of maintaining the integrity of these utilities for the benefit of society. However, this integrity is often compromised during excavation works when a utility is struck. In the Netherlands, there were approximately 47,000 such incidents in 2022, averaging over a hundred daily. These damaged cables or pipelines disrupt the services they provide but also compromise the safety of construction workers who face risks from, predominantly, damaged gas or electricity lines. These alarming figures fueled my desire to help prevent such damages. Therefore, I immediately accepted when Professor André Dorée offered me a PhD position in 2019 to explore and support the utility surveying process through ground penetrating radar (GPR). The inadequacy of current methods to survey cables and pipelines before excavation was the practical starting point for my research. Utility maps can be inaccurate or incomplete; trial trenches are costly and only provide localized information.

GPR – the primary focus of this PhD research – is a technology that I and many fellow scholars believe can be pivotal in reducing excavation-related damages to utilities. Given that this technology is unfamiliar to many, allow me to provide a brief introduction. GPR is a technology encapsulated in a device that I often describe to those around me as "a machine resembling a lawnmower in size but functioning like an MRI scanner for the underground." This 'lawnmower,' however, has been significantly underutilized in practice, and even the institutional framework in the Netherlands appears to lack confidence in it. Despite their disadvantages, trial trenches are the norm; some construction organizations even mistakenly believe them to be mandatory. So, work is needed to change this.

Through my work in this dissertation, I have taken a modest step toward that change. Grounded in the belief that GPR can substantially improve our current surveying practice, I have discerned when, where, and how this technology can be of value to surveying practices. Those questions were at the heart of this dissertation, and they set in motion a process spanning over four years. Over these four years, I have had a transformative journey with GPR. Starting as a novice, I have evolved into a proficient GPR operator and introduced the technology on various construction sites. I have seen firsthand how a technology that was initially contested eventually became part of the operational procedures of organizations that had never used GPR before. These real-life experiences of local practices have been invaluable in unraveling the most effective GPR deployment strategies at each construction site I visited.

I have distilled the GPR deployment strategies into developing machine learning-driven decision support and guidance. The resulting decision model is expected to aid construction practitioners in making better-informed decisions on the deployment of GPR. I believe this marks a significant step toward expediting the uptake of GPR as a surveying method. A major hurdle has consistently been the lack of knowledge among practitioners regarding how to use this technology. The model helps them overcome this knowledge gap, thereby setting a step toward improving the GPR surveying practice and hopefully contributing to a reduction in excavation-related damages to utilities.

I sincerely hope that you, the reader, will find value in the journey in this dissertation. In its chapters, you will encounter my research’s theoretical and practical contributions and a narrative that encompasses my personal journey. Enjoy your reading!

With warm regards,

Ramon ter Huurne

Summary

Utility strikes pose a substantial challenge in the construction industry. In 2022, the Netherlands alone reported approximately 47 thousand such incidents. These result in cost overruns, service disruptions, environmental damage, and safety risks. While utility maps and trial trenches (i.e., cut and cover excavation) are typically used to survey utilities before excavation work, these methods often fall short. Utility maps can be inaccurate or incomplete, and trial trenching is intrusive, disruptive, and location-specific. The geophysical ground penetrating radar (GPR) method offers a non-intrusive and rapid alternative to those methods; it can improve utility surveying practices and help reduce utility strikes.

While research is abundant on advancing GPR from a technological standpoint, there is an insufficient understanding of its local use dynamic within construction site settings. There is a lack of insight into how the technology influences, and is influenced by, practical construction site situations such as utility surveying practices. This, in turn, has led to an insufficient understanding among construction practitioners of when, where, and how to deploy GPR, resulting in numerous failed applications of the technology in the field. Consequently, despite its potential benefits, GPR has faced limited adoption.

This dissertation addresses the gap by providing context-rich, practice-based insights into how GPR influences and enriches surveying practices. These insights enhance our socio-technical understanding of the advantages and challenges associated with GPR-enhanced utility surveying. To tackle the lack of understanding among practitioners regarding GPR deployment, these insights are used to develop operational decision support and guidance for construction workers using GPR onsite. Therefore, the objective of this PhD research is as follows:

To explore and support ground penetrating radar-enhanced utility surveying practices.

The dissertation is structured into five studies, grouped into two research phases: problem exploration and support development. In the problem exploration phase, I used practice-based theories to develop socio-technical insights into the local use dynamics of GPR. These insights focused on how GPR impacts and contributes to surveying practices and how practitioners foresee GPR's role in their future activities. This phase began by examining the structure of the Dutch utility surveying practice, which was the case studied in this research. I then explored the local use dynamics of GPR at construction sites using a *technology-in-practice* perspective. From this perspective, I introduced GPR to thirteen construction sites across the Netherlands and collaborated with construction practitioners on 125 surveying activities. Together with these practitioners, I assessed how GPR could be most effectively deployed at each site. The first three studies of this dissertation detail this exploratory process:

[1.] This first study provides a contextual outlook on the structure of the Dutch utility surveying practice and elucidates GPR's role therein. Using international surveying frameworks – including the British PAS 128, American ASCE 38-02, Australian AS 5488, and Malaysian Standard Guideline – as an analytical lens, this study concludes that the Dutch practice primarily benefits from utility plans, verified through trial trenches. Driven by regulatory requirements and legal obligations, the Dutch practice has a seemingly constrained structure that marginalizes the use of the geophysical GPR method. This characterizes GPR as an emerging technology for the Dutch practice.

[2.] The second study provides an empirical, conceptual model of early-stage innovation adoption dynamics (i.e., the stage before the formal decision to adopt is made), unraveling the early interactions between utility surveying routines and GPR technology. Using the theoretical lens of routine dynamics, it identifies triggers for change (i.e., disruptions and shortcomings) within the Dutch utility surveying routine, facilitating the practical exploration and use of GPR. It illuminates the conditions in which the use of GPR was considered favorable by practitioners and concludes that the Dutch surveying practice is receptive to its uptake.

[3.] The third study provides a bespoke participatory take on Cultural Historical Activity Theory's method of formative interventions to identify potential future impacts of emerging technologies, like GPR. It details how researchers can shape conditions for emerging technology to be considered by practitioners, expose tensions within existing activities to support practitioners in recognizing problem situations, assist practitioners with emerging technology to resolve those problems, act as operators of the technology to facilitate its exploration, and facilitate practitioner's reflection on the existing activity. Utilizing this bespoke interventionist approach, the study concludes that GPR can be integrated into utility surveying activities in three ways: as an additional, supportive, or replacement tool for trial trenches.

The practice-based insights from the first three studies identified three GPR deployment strategies. In the support development phase of this PhD research, these strategies were outlined in a dataset and supplemented with methods for GPR deployment: using it as a standalone surveying method with post-processing radargrams, a standalone method without post-processing radargrams, or a complementary method alongside trial trench verification. Subsequently, various types of decision models were developed and assessed to determine which type of model best predicts the appropriate GPR method for new utility surveying activities. This phase is described in two studies:

[4.] The fourth study outlines an empirically rich dataset that encompasses all 125 utility surveying activities examined in the study. This dataset details the chosen GPR deployment method for each GPR deployment strategy, the collected radargrams and trial trench data, and the metadata related to the construction context, geophysical setting, utility infrastructure present, and technical specifications of the GPR equipment used. Unlike controlled or laboratory-based settings, this dataset originates from practical construction site settings, providing valuable empirical insights into the actual use of GPR in surveying practices.

[5.] The fifth study describes the development and assessment of expert-based and generalized machine learning-driven decision models to support construction practitioners in choosing the appropriate GPR deployment method for their surveying activities. These include the expert-based Case-Based Reasoning (CBR) and generalized Decision Trees (DT), Random Forest (RF), and Support Vector Machine (SVM) models. Using the dataset outlined in the fourth study, the study concludes that CBR is the most effective model for onsite GPR decision-making. This suggests that context-based onsite decision-making issues may still benefit most from expert knowledge-capturing models.

The five research studies together provide empirically rich, socio-technical knowledge that clarifies the use of GPR in utility surveying practices. They culminated in a decision-making model for GPR-enhanced utility surveying, designed to support onsite decision-making during utility surveying practices. Once applied in construction, the model is poised to support utility surveyors, contractors, utility owners, and any other organization involved in excavation through a potentially more effective use of GPR. This is expected to help in the construction sector's desire to reduce utility strikes and improve work productivity.

However, beyond the five studies, this dissertation also suggests a lack of knowledge development and legitimacy for GPR within the Dutch underground infrastructure domain, hindering its widespread adoption. Therefore, it emphasizes that it is essential to convey a realistic understanding of GPR's capabilities and limitations to industry practitioners. The technology is not a 'magical box' but rather a tool with technical limitations. This dissertation provided empirical evidence that GPR functions best as a tool used alongside trial trenches rather than as a standalone solution. Research institutes and industry associations thus play a crucial role in raising awareness and facilitating learning about GPR. This involves equipping practitioners with the necessary skills and assisting organizations with developing new procedures for effective GPR integration.

In conclusion, this dissertation contributes to both the construction research domain and utility sector by offering conceptualizations of early-stage innovation adoption dynamics, a bespoke methodological approach to study emerging technologies, evidence for using expert-based decision models to effectively capture intricate context-based decision problems, and practical tools and

knowledge for navigating underground utilities with GPR. These contributions have the potential to expedite the adoption of GPR, thereby enhancing the effectiveness, efficiency, and safety of utility surveying practices. To realize this potential, it is essential to communicate a realistic understanding of GPR's value within the surveying context, implement systemic changes to enhance its legitimacy, and educate practitioners and organizations on its use. The insights presented in this dissertation can serve as a valuable resource in this regard.

Samenvatting

Graafschades aan ondergrondse infrastructuur vormen een aanzienlijke uitdaging in de bouw. In 2022 werden in Nederland alleen al ongeveer 47 duizend graafschades gerapporteerd. Deze incidenten leiden tot kostenoverschrijdingen, verstoringen van diensten, omgevingsschade en veiligheidsrisico's. Hoewel men met het gebruik van kaarten van kabels en leidingen en het graven van proefsleuven (d.w.z., het fysiek blootleggen van kabels en leidingen) probeert de infra in kaart te brengen vóór graafwerkzaamheden, schieten deze methoden vaak tekort. Kaarten kunnen onnauwkeurig of onvolledig zijn, en proefsleuven zijn invasief, verstorend en locatie-specifiek. De geofysische grondradar (ground penetrating radar, GPR) biedt een niet-invasief en snel alternatief voor deze methoden.

Hoewel er veel onderzoek wordt gedaan naar de technologische verbetering van GPR als lokaliseringsmethode, is er echter onvoldoende begrip over het lokale gebruik van GPR op de bouwplaats. Er ontbreekt inzicht in hoe de technologie de praktijk beïnvloedt, zoals bij het in kaart brengen van kabels en leidingen, en hoe de praktijk de technologie beïnvloedt. Dit heeft geleid tot een gebrek aan kennis onder professionals over wanneer, waar en hoe GPR te gebruiken, resulterende in vele mislukte toepassingen van de technologie. Hierdoor kent GPR, ondanks de potentiële voordelen, vooralsnog beperkte adoptie.

Dit proefschrift vult deze kloof door contextrijke, praktijkgerichte inzichten te bieden in hoe GPR de lokaliseringspraktijk van kabels en leidingen beïnvloedt en verrijkt. Deze inzichten vergroten ons begrip van de voordelen en uitdagingen van GPR-ondersteunde lokalisering vanuit een socio-technisch perspectief. Om het gebrek aan kennis onder professionals over het gebruik van GPR aan te pakken, worden deze inzichten gebruikt om operationele beslisondersteuning te ontwikkelen voor het gebruik van GPR op de bouwplaats. Het doel van dit promotieonderzoek is dan ook als volgt:

Het verkennen en ondersteunen van grondradar-ondersteunde lokaliseringspraktijken van kabels en leidingen.

Het proefschrift is opgebouwd uit vijf studies, verdeeld over twee onderzoeksfasen: probleemverkenning en oplossingontwikkeling. In de probleemverkenningsfase heb ik praktijkgerichte theorieën toegepast om socio-technische inzichten te verkrijgen in de lokale gebruiksdynamiek van GPR. Deze inzichten belichten hoe GPR de lokaliseringspraktijk beïnvloedt en verrijkt, en verklaren hoe professionals de rol van GPR in hun toekomstige werkzaamheden zien. De fase begon met een verkenning van de structuur van de Nederlandse lokaliseringspraktijk, die als casus voor dit onderzoek diende. Daarna onderzocht ik de lokale gebruiksdynamiek van GPR vanuit een *technology-in-practice* perspectief. Dit hield in dat ik GPR introduceerde op dertien bouwplaatsen in Nederland en samenwerkte met professionals aan 125 lokaliseringsactiviteiten. Samen met deze professionals

beoordeelde ik op elke locatie hoe GPR het meest effectief kon worden geïmplementeerd. De eerste drie studies van dit proefschrift beschrijven dit verkennende proces.

[1.] De eerste studie biedt een overzicht van de structuur van de Nederlandse lokaliseringspraktijk van kabels en leidingen en verduidelijkt de rol van GPR daarin. Door gebruik te maken van internationale lokaliseringskaders als analytische lens – waaronder de Britse PAS 128, de Amerikaanse ASCE 38-02, de Australische AS 5488 en de Maleisische Standaardrichtlijn – concludeert deze studie dat de Nederlandse praktijk voornamelijk vertrouwt op de liggingsdata van kabels en leidingen op kaarten, die worden geverifieerd door proefsleuven. Gedreven door regelgeving en wettelijke verplichtingen heeft de Nederlandse praktijk een ogenschijnlijk beperkende structuur die de inzet van GPR marginaliseert. Dit plaatst GPR als een opkomende technologie binnen de Nederlandse context.

[2.] De tweede studie biedt een empirisch, conceptueel model van de dynamiek van vroegtijdige innovatie-adoptie (d.w.z., de fase voordat formeel wordt besloten tot adoptie over te gaan), waarbij de interacties tussen routines van lokaliseren en GPR-technologie worden ontrafeld. Met behulp van de theoretische lens van routinedynamiek identificeert het triggers voor verandering (d.w.z., verstoringen en tekortkomingen) binnen lokaliseringsroutines die de praktische verkenning en het gebruik van GPR stimuleren. Het belicht de omstandigheden waaronder het gebruik van GPR door professionals als waardevol werd beschouwd en concludeert dat de Nederlandse praktijk ontvankelijk is voor het gebruik ervan.

[3.] De derde studie presenteert een specifieke participatieve benadering van ‘formative interventions’ binnen de Culturele Historische Activiteitstheorie om de toekomstige impact van opkomende technologieën, zoals GPR, te verkennen. Het beschrijft hoe onderzoekers kunnen zorgen dat deze technologieën door professionals worden overwogen, hoe spanningen binnen bestaande activiteiten kunnen worden blootgelegd om problemen te identificeren, hoe professionals ondersteund kunnen worden bij de toepassing van deze technologieën, hoe onderzoekers als operators kunnen optreden om de verkenning van technologieën te bevorderen, en hoe zij de reflectie van professionals op bestaande activiteiten kunnen stimuleren. Door het gebruik van deze specifieke interventionistische benadering, concludeert deze studie dat GPR op drie manieren kan worden geïntegreerd tijdens het lokaliseren van kabels en leidingen: als aanvullend, ondersteunend of vervangend middel voor proefsleuven.

De praktijkgerichte inzichten uit de eerste drie studies identificeerden drie GPR-implementatiestrategieën. In de oplossingsontwikkelingsfase van dit PhD-onderzoek werden deze strategieën vastgelegd in een dataset en aangevuld met methoden voor de toepassing van GPR: het gebruik van GPR als een zelfstandige methode met nabewerking van radargrammen, een zelfstandige methode zonder nabewerking van radargrammen, of een aanvullende methode naast proefsleuven. Vervolgens werden verschillende beslismodellen ontwikkeld en geëvalueerd om te bepalen welk type model het beste voorspelt welke GPR-methode te gebruiken bij nieuwe lokaliseringsactiviteiten. Deze fase wordt in twee studies beschreven:

[4.] De vierde studie beschrijft een empirisch rijke dataset die alle 125 lokaliseringsactiviteiten omvat die in het onderzoek zijn onderzocht. Deze dataset bevat voor elke GPR-implementatiestrategie de gekozen GPR-methode, de verzamelde radargrammen en proefsleufgegevens, en metadata met betrekking tot de bouwcontext, geofysische setting, aanwezige infra en technische specificaties van de gebruikte GPR-apparatuur. In tegenstelling tot gecontroleerde omgevingen, biedt de dataset daarmee waardevolle empirische inzichten in het daadwerkelijke gebruik van GPR tijdens lokaliseringspraktijken.

[5.] De vijfde studie beschrijft de ontwikkeling en evaluatie van zowel expert-gebaseerde als generaliserende machine learning-gedreven beslismodellen ter ondersteuning van professionals bij het kiezen van een GPR-methode. Dit omvat de expert-gebaseerde Case-Based Reasoning (CBR) en de generaliserende Decision Trees (DT), Random Forest (RF) en Support Vector Machine (SVM) modellen. Op basis van de dataset die in de vierde studie wordt beschreven, concludeert de studie dat CBR het meest effectieve model is voor beslisondersteuning bij het gebruik van GPR. Dit suggereert dat contextgebonden besluitvormingsproblemen op de bouwplaats nog steeds het meeste baat kunnen hebben bij modellen die expertkennis vastleggen.

De vijf studies samen bieden empirisch rijke, socio-technische kennis over het gebruik van GPR bij het lokaliseren van kabels en leidingen. Deze inzichten hebben geleid tot de ontwikkeling van een beslismodel voor GPR-ondersteunend lokaliseren. De toepassing van dit model op de bouwplaats ondersteunt landmeters, aannemers, netbeheerders en elke andere organisatie die betrokken is bij graafwerkzaamheden door een mogelijk effectievere inzet van GPR. Dit zal naar verwachting helpen bij de wens van de bouwsector om graafschades te verminderen en de productiviteit te vergroten.

Echter, naast de vijf studies wijst dit proefschrift ook op een tekort aan kennisontwikkeling en legitimiteit voor GPR binnen de Nederlandse context. Dit belemmert de bredere adoptie van de technologie. Daarom is het essentieel om een realistisch begrip van de mogelijkheden en beperkingen van GPR over te brengen aan de praktijk. GPR is geen ‘magische doos,’ maar een hulpmiddel met technische beperkingen. Dit proefschrift toont aan dat GPR het meest effectief wordt gebruikt als aanvulling op proefsleuven, in plaats van een op zichzelf staande methode. Onderzoeksinstituten en brancheverenigingen spelen dan ook een cruciale rol in het vergroten van het bewustzijn en het faciliteren van leren over GPR. Dit houdt in dat professionals worden uitgerust met de nodige vaardigheden en organisaties worden ondersteund bij het ontwikkelen van nieuwe procedures voor een effectieve integratie van GPR.

Concluderend draagt dit proefschrift bij aan zowel lopend onderzoek als de Nederlandse bouwsector door inzicht te geven in vroege innovatie-adoptie dynamieken, een specifieke methodologische aanpak te bieden voor het bestuderen van opkomende technologieën, bewijs te leveren voor het effectieve gebruik van expert-gebaseerde beslismodellen bij contextgebonden besluitvormingsproblemen, en praktische hulpmiddelen te verschaffen voor het lokaliseren van ondergrondse infra met GPR. Tezamen kan deze nieuwe kennis helpen de adoptie van GPR te versnellen en daarmee de effectiviteit, efficiëntie en veiligheid van lokalisering te verbeteren. Om dit te realiseren, is het echter essentieel om een realistisch begrip van de waarde van GPR over te brengen naar de bouwsector, de legitimiteit van de technologie te vergroten, en professionals en organisaties op te leiden in het gebruik ervan. De inzichten uit dit proefschrift kunnen hierbij een waardevolle bijdrage leveren.

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List of acronyms

CBR	Case based reasoning
CHAT	Cultural Historical Activity Theory
DSR	Design Science Research
DSRM	Design Science Research Methodology
DT	Decision tree
GPR	Ground penetrating radar
SVM	Support vector machine

Chapter 1

introduction

1. Introduction

Damaging the sheath of a utility or snapping a utility line entirely is termed a ‘utility strike.’ In 2022, approximately 47 thousand of these strikes were reported in the Netherlands (RDI, 2023). These accounted for 5.6% of all excavation works and resulted in direct repair costs of 38 million euros. The additional indirect costs, often termed ‘real’ or ‘societal’ costs, can multiply these direct costs by a factor of up to 29 (Makana et al., 2016). Similarly concerning figures are reported in other countries; for instance, Canada and the United States recorded over 213,000 utility strikes in 2022 (CGA, 2023). Utility strikes thus present a significant challenge to the construction sector, causing substantial financial losses while also disrupting utility services, disturbing the local environment, and endangering bystanders.

As societies continue to grow and urbanize, communication technologies advance, and long-term agendas such as the energy transition and climate adaptation are actively underway (European Commission, 2021), construction projects increasingly include works with or near subsurface utilities. This trend, coupled with tight budgets, schedules, and labor shortages, challenges organizations to navigate the intricate world of subsurface infrastructure effectively. To safeguard this infrastructure amid the increasing operational pressure, construction organizations need accurate and complete information about the utilities’ whereabouts.

The ground penetrating radar (GPR) is widely regarded as a promising method to support the construction sector in utility localization (Lai et al., 2018; Metje et al., 2007, 2015; Ristić et al., 2017). GPR is a geophysical method that offers a rapid and non-intrusive way to detect utilities. The technology works by sending an electromagnetic signal into the subsurface. Changing electric and dielectric properties of the subsurface medium cause the signal to scatter and reflect to the GPR’s receiver. These reflections – for utilities typically visible in hyperbolic shapes – provide the basis for imaging a ‘radargram.’ From this radargram, utility depth and, to a lesser extent, size, and material can be inferred (Daniels, 2008; Jol, 2009).

While ample research efforts have been directed at advancing GPR from a technological standpoint, its local use dynamic within construction site settings remains inadequately understood. There is a lack of insight into how the technology influences and is influenced by practical construction site situations such as utility surveying practices. Consequently, construction practitioners have an insufficient understanding of when, where, and how to deploy GPR. This has resulted in numerous failed applications of the technology in the field. As a result, despite its potential benefits, GPR adoption has been limited (Lai et al. 2018), and, hence, is still considered an emerging technology.

To address this gap, this dissertation contributes context-rich, practice-based insights into how GPR impacts and contributes to surveying practices. It aims to deepen our socio-technical understanding of the benefits and challenges associated with GPR-enhanced utility surveying and offer operational decision support and guidance for its effective integration into surveying practices. These contributions seek to aid construction practitioners in effectively deploying GPR, potentially boosting its adoption, enhancing utility localization, and ultimately reducing utility strikes.

The following sections explore this aim within a defined theoretical and practical context. This is followed by an explanation of the adopted research philosophy, after which the dissertation's primary research objective and sub-objectives are introduced. The research methodology is then presented, and the chapter concludes by outlining the structure of the dissertation.

1.1. Theoretical context

To gain a deeper understanding of technology's impact and contributions in practice, construction management literature emphasizes context-rich, practice-based studies of innovation (Shibeika & Harty, 2015). So far, such studies on GPR are scarce. Instead, abundant research focuses on enhancing GPR's utility detection capabilities from a technological standpoint. The emphasis on these technically oriented studies can be attributed to GPR's inherent limitations and uncertainties. Factors such as soil type, moisture content, and density can impact its performance, resulting in signal issues (Costello et al., 2007; Daniels, 2008; Jol, 2009; Metje et al., 2008). Moreover, when multiple buried utilities are close, GPR images can become cluttered with overlapping hyperbolic signatures (Costello et al., 2007).

The current body of research aims to address these uncertainties through innovative technical solutions. For instance, studies have been conducted to optimize data processing techniques (Ghanbari et al., 2022) and explore innovative scanning approaches (Siu & Lai, 2019). While these research endeavors significantly advanced GPR from a technical standpoint, they occur in controlled, laboratory-like settings and do not consider the GPR's socio-technical aspects within practical construction site settings. Consequently, there remains a lack of insight into how the technology influences and is influenced by practical construction site situations such as utility surveying practices.

To fill this gap, I use practice theory to understand how GPR impacts surveying practices and how practitioners foresee its future role. Practice theory posits that social life emerges through people's everyday actions, which are consequential in shaping social structures (Feldman & Orlikowski, 2011). It emphasizes the mutual constitution of phenomena, rejecting dualisms and recognizing the inherent relationship between elements such as structure and agency. To study GPR through this lens, I specifically adopt Orlikowski's (2000) technology-in-practice perspective. This perspective distinguishes between technology as a tangible *technological artifact* (e.g., a machine, technique, or device) and *technology-in-practice*, which is the interaction structure enacted when people use the artifact in their everyday situated activities. This perspective allows for a deep understanding of the interactions between individuals and GPR technology, focusing on how their engagement continually shapes and reshapes its use in real-world practices.

While practice theory offers distinct pathways, I use the theoretical lenses of routine dynamics and Cultural Historical Activity Theory (CHAT) to explore the interaction structure enacted when people use GPR. By conceptualizing this technology-in-practice enactment as a black box, I leveraged both lenses to gain socio-technical insights (i.e., problem exploration). These insights were crucial in identifying GPR deployment strategies that directly informed the technical development of decision support and guidance tools using construction automation solutions (i.e., support development). The alignment between both phases is twofold: the practice-based studies provide a comprehensive understanding of practical challenges and user interactions, while the technical studies translate these insights into actionable deployment strategies and technological solutions. The theoretical concepts and their interrelationships are visualized in Figure 1 and elaborated upon below.

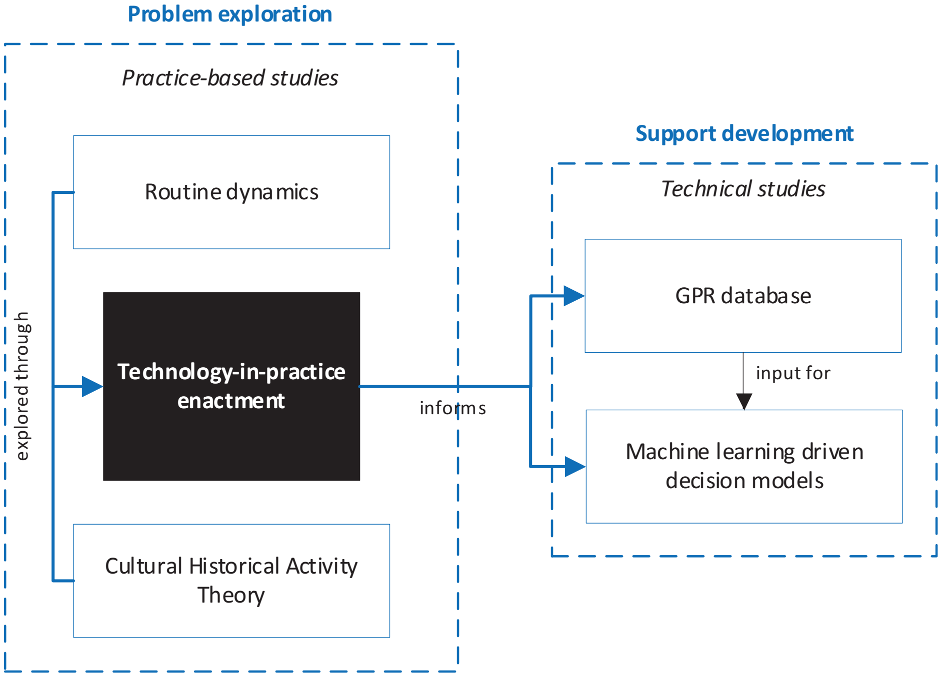


Figure 1. Theoretical context of this dissertation.

1.1.1. Routine dynamics

The introduction of GPR into the well-established utility surveying practice is anticipated to have a disruptive impact, given that traditional surveying methods such as trial trench digging and utility maps have long been the norm (Costello et al., 2007; Thomas et al., 2009). Many construction organizations are thus unfamiliar with GPR and have not adapted their ongoing processes to incorporate this emerging technology into their surveying practices. Therefore, in this dissertation, I first delve into the local use dynamics of GPR to unravel the early interactions between utility surveying routines and GPR technology.

Routine dynamics provides a valuable theoretical lens to achieve this. The lens focuses on the interaction between the routinized work processes and the emerging technology (Feldman et al., 2019). Such routines are repetitive, recognizable, and interdependent patterns of actions that revolve around stability and change mechanisms (Becker, 2004; Feldman et al., 2016). Using these mechanisms as a theoretical lens has proven effective in unraveling organizational and operational change (e.g., Bygballe et al. 2021; Danner-Schröder and Geiger 2016; Turner and Rindova 2012).

In this dissertation, I use this lens to collect insights into construction workers' thoughts (i.e., cognition) and actions when encountering GPR technology in the field. I use the lens to identify triggers that initiate either stability or change of the utility surveying routine. Through these socio-technical insights, I aim to illuminate the utility surveying conditions in which GPR is considered favorable by practitioners, to understand when local surveying practices are receptive to its uptake. This, in turn, facilitates an initial understanding of GPR's impacts and contributions to surveying practices.

1.1.2. Activity theory

Integrating GPR into surveying routines is expected to transform traditional surveying practices significantly, representing a radical departure from conventional methods. To deepen our insight into how GPR influences and is influenced by practical construction site situations such as utility surveying practices, it is essential to comprehend this transformative influence of GPR. This understanding will not only help unravel the impacts and contributions of the technology but also elucidate the appropriate contexts and methods that determine the effective deployment of GPR within utility surveying practices. I used real-world interventions guided by CHAT to develop this comprehensive understanding.

CHAT aims to understand change by focusing on activities. It describes activities as a system of a shared objective that drives people to interact and work together in complex contexts, supported by tools like GPR technology. It emphasizes how these tools mediate the pursuit of the objectives, during which activities and their elements may get exposed to changing contexts (Engeström & Sannino, 2021; Miettinen et al., 2012). The activity theoretical framework by Engeström (2015) captures how these changes unfold at the activity system level.

As emerging technologies like GPR are typically not yet integrated into ongoing activities, passive observations alone cannot study their future impacts. Instead, researchers must actively confront present-day activities to assess their possible future impacts. This resonates with the interventionist epistemology of CHAT (Engeström et al., 2014; Sannino, 2011; Sannino et al., 2016), which postulates that interventions may disrupt an activity and initiate change. Interventions thus generate opportunities to break away from and transform the given activity system.

This type of interventionist approach is underexplored in the construction management literature, yet could offer a context-rich, practice-based perspective that helps unravel practitioners' early (i.e., preadoption) perspectives on the role of technology in their future activities. The case of GPR presents a unique opportunity to investigate the methodological underpinnings of the interventionist approach while concurrently complementing the initial understanding of GPR's impacts and contributions to surveying practices acquired earlier using the lens of routine dynamics.

1.1.3. Construction Automation

The socio-technical insights collected through the technology-in-practice perspective inform the technical development of operational decision support and guidance. Advancements in computing power have enabled machine learning solutions to develop such decision models. Two main groups categorize these models: expert-based and generalized. While previous construction automation studies have showcased the effectiveness of expert-based machine learning decision models (e.g., Ng and Luu 2008), generalized decision models, including Decision Trees, Random Forest, and Support Vector Machine algorithms, have also demonstrated strong performance across a broad spectrum of construction decision problems (Kim et al., 2022; Koo et al., 2019; Shin et al., 2012).

The field of construction automation research currently offers limited insights into the operational deployment of GPR in surveying practices. This aligns with the broader trend observed in the construction automation literature, highlighting the scarcity of studies focused on enhancing onsite operational decision-making through automation (Xu et al., 2021). This scarcity, especially within the context of GPR, may be attributed to the initial deficiency of available data essential for developing such automation solutions.

The technology-in-practice perspective helps to collect this necessary data. However, the question remains as to which type of machine learning-driven decision models excel in supporting the use of GPR. An assessment of expert-based or generalized decision models is required to determine whether and which type of machine learning can best contribute to developing effective decision support and guidance for GPR-enhanced utility surveying.

In short, this dissertation aims to contribute to the evolving field of GPR-based utility surveying through a combination of theoretical analysis, empirical research, and automation solutions. By examining the interplay between routines, activity systems, and machine learning-driven decision support, I seek to deepen our understanding of the local use dynamics of GPR and use these socio-technical insights to develop operational decision support for construction workers when deploying GPR onsite. The next section provides further motivation for this development from a practical context.

1.2. Practical context

The practical motivation to develop such support and guidance is threefold: [1] to reduce utility strikes, we need to [2] overcome the drawbacks of traditional surveying methods by [3] supporting construction workers in their effective deployment of GPR-enhanced surveying practices. The following sections elaborate on this line of argument and introduce the case of my research.

Around the world, (subsurface) utilities are essential to the functioning and development of our society. These infrastructures include water and sewage systems, electrical and telecommunication cables, and gas and heating pipelines. They provide vital services such as clean water supply, energy distribution, and communication connectivity. Utilities, hence, form the backbone of modern life. As illustrated earlier, utility strikes significantly challenge the construction sector and threaten utility infrastructure.

Improving the surveying practice is expected to reduce the occurrence of these utility strikes. In many countries, the traditional utility surveying practice relies on a combination of trial trenching and utility maps. Yet, this approach has several drawbacks (Racz, 2017). Trial trenching is disruptive, expensive, labor-intensive, and provides only localized insights (Costello et al., 2007; Metje et al., 2007). Additionally, it risks damaging utilities as it involves further ground excavation. On the other hand, utility maps often do not reflect the as-built situation, as they tend to be incomplete or inaccurate (Thomas et al., 2009).

The use of GPR is expected to help overcome these current drawbacks and improve the surveying practice. Offering a ‘trenchless’ surveying alternative, construction organizations can use GPR to acquire a comprehensive coverage of construction sites, in a rapid and non-intrusive manner (Lai et al., 2018; Lester & Bernold, 2007; Metje et al., 2007). However, effective deployment of GPR-enhanced surveying practices requires construction practitioners to have construction expertise and an understanding of how the (geo)physical context impacts GPR outcomes. The absence of such knowledge is a common issue on construction sites, resulting in numerous failed applications of the technology in the field (Lai et al., 2018).

This practical context drives the objective of this dissertation to unravel GPR's socio-technical aspects and use these to develop support and guidance for construction workers to effectively deploy GPR into surveying practices. The Netherlands was chosen as a case study. This is for two primary reasons. First, utility surveying practices in the Netherlands seemingly rely on a combination of trial trenching and utility maps. The adoption of GPR by Dutch construction organizations is limited, leading to a lack of experience and expertise in utilizing GPR technology effectively. This situation motivates the development of decision support and guidance while also providing an environment where changing routines and transforming surveying activities can be extensively studied.

Second, the Netherlands boasts an extensive network of underground cables and pipelines, covering 1.7 million kilometers. Utility strikes pose a significant challenge to the dense and complex Dutch underground infrastructure. As previously mentioned, nearly 47 thousand strikes were reported in the Netherlands in 2022, and these numbers are not decreasing, according to recent statistics (RDI, 2023). With transitions in energy, climate, and green initiatives, the demand for underground work is expected to rise, further compounding this challenge. At the same time, labor availability is on the decline, resulting in more work being handled by fewer people amid increasing time and financial constraints. Faced with labor market shortages and a pressing need to reduce utility strikes, there is a growing interest in innovative solutions that can enhance safety and productivity. This pursuit of 'new ways of working' incentivizes organizations to explore the use of GPR in their daily practices, allowing me to collect the necessary data for this dissertation.

In short, the practical motivation for exploring and supporting GPR-enhanced utility surveying stems from the desire to improve the established surveying practice and reduce utility strikes. This research posits that GPR can play a vital role in achieving this, and the development of support and guidance for construction workers to deploy GPR effectively can expedite this process.

1.3. Research philosophy

The technology-in-practice perspective adopted in this dissertation stems from my belief that established findings should be theoretically sound, grounded in empirical data and systematic analysis, and directly relevant to the construction practice. My objective as a researcher thus extends beyond producing theoretical insights. Through this dissertation, I aim to deepen our understanding of the benefits and challenges associated with GPR-enhanced utility surveying and provide practical support and guidance for its effective integration into surveying practices. Since GPR has not yet achieved widespread adoption, I undertook the role of bringing GPR to the construction site to study its impacts and contributions firsthand. I engaged actively with construction practitioners onsite to explore GPR's local use dynamics.

My approach aligns closely with a pragmatism philosophy. Pragmatism, rooted in the ideas of Peirce (1878), emphasizes that the true understanding of a concept or idea comes from its practical application or use in real-world situations. Pragmatism and practice theory are well-aligned in research philosophy, as both stress the importance of practical, real-world contexts and experiences in understanding social phenomena. Specifically, pragmatism prioritizes the practical application and utility of knowledge, rooted in the belief that knowledge is validated through its practical consequences.

This pragmatic approach led me to immerse myself actively in the field alongside GPR. By engaging directly with the technology in real-world settings, I gained firsthand experience and socio-technical insights that informed the development of practical, technological solutions. This hands-on approach enabled me to bridge theory and practice, ensuring that the development of socio-technical knowledge and decision support and guidance tools were grounded in practical realities and responsive to the needs of the field.

As an immersive researcher, my approach also draws inspiration from Van de Ven's (2007) engaged scholarship concept. Engaged scholarship emphasizes the active involvement of the researcher in understanding diverse perspectives to address real-world challenges. This approach transcends traditional academic research, aiming to make a tangible impact on society and practice by directly engaging with those involved in the research.

1.4. Research goal and objectives

The theoretical and practical contexts outlined in the preceding sections underscore the need for a thorough practice-based exploration into how GPR impacts and contributes to surveying practices and how practitioners foresee its role in their future activities (i.e., problem exploration). By examining the interplay between routines, activity systems, and machine learning-driven decision support, I aim to develop comprehensive decision support and guidance that facilitates the effective deployment of GPR-enhanced utility surveying (i.e., support development).

The theoretical and practical contributions of this dissertation aim to enhance the utility surveying process, making it more effective, efficient, and safe, ultimately aiming to reduce utility strikes. Following this notion, this dissertation addresses the following research objective:

To explore and support ground penetrating radar-enhanced utility surveying practices.

To achieve the primary research objective, I formulated five distinct research objectives. Achieving these objectives progressively builds knowledge, theory, and practical tools for enhancing GPR-enhanced utility surveying practices. Figure 2 visually connects the five objectives and links them to the overarching motivation behind this dissertation: enhancing the utility surveying practice and reducing utility strikes. The five objectives are:

[1.] To explore the structure of the Dutch utility surveying practice and GPR's role within its arrangement (Chapter 2);
[2.] To unravel the early interactions between utility surveying routines and GPR and identify triggers that either obstruct or facilitate its practical exploration and adoption (Chapter 3);
[3.] To identify the future impacts and transformative potential of GPR on utility surveying practices and clarify how practitioners foresee GPR's role in their future activities (Chapter 4);
[4.] To outline local GPR deployment strategies into a dataset that details the construction site setting, serving as input for the development of machine learning-driven decision models (Chapter 5);
[5.] To assess the effectiveness of both expert-based and generalized machine learning-driven decision models in supporting construction practitioners with GPR deployment during utility surveying activities (Chapter 6).

1.5. Research methodology

To achieve the primary research objective of this dissertation, and in alignment with my pragmatism research philosophy and technology-in-practice perspective, I conducted a Design Science Research (DSR) study guided by Hevner's (2007) perspectives. Hevner's DSR perspective emphasizes creating knowledge and understanding to design and construct artifacts, such as decision support models, effectively. For this DSR study, I adopted the Design Science Research Methodology (DSRM) proposed by Peffers et al. (2014), which aligns with Hevner's views. Throughout this dissertation, I follow five phases as outlined in the DSRM by Peffers, which include [1] problem identification and motivation, [2] definition of objectives, [3] design and development, [4] demonstration, and [5] evaluation.

For the problem identification and motivation phase, I began by exploring the structure of the utility surveying practice in the Netherlands from an institutional, organizational, and operational perspective (Chapter 2). This involved consulting national legislation, directives, and arrangements made by organizations for utility surveying and visiting utility surveying practices in the field. These efforts provided valuable insights into the existing Dutch surveying practice, helped confirm the limitations and challenges associated with the current surveying approach, and clarified the role of GPR.

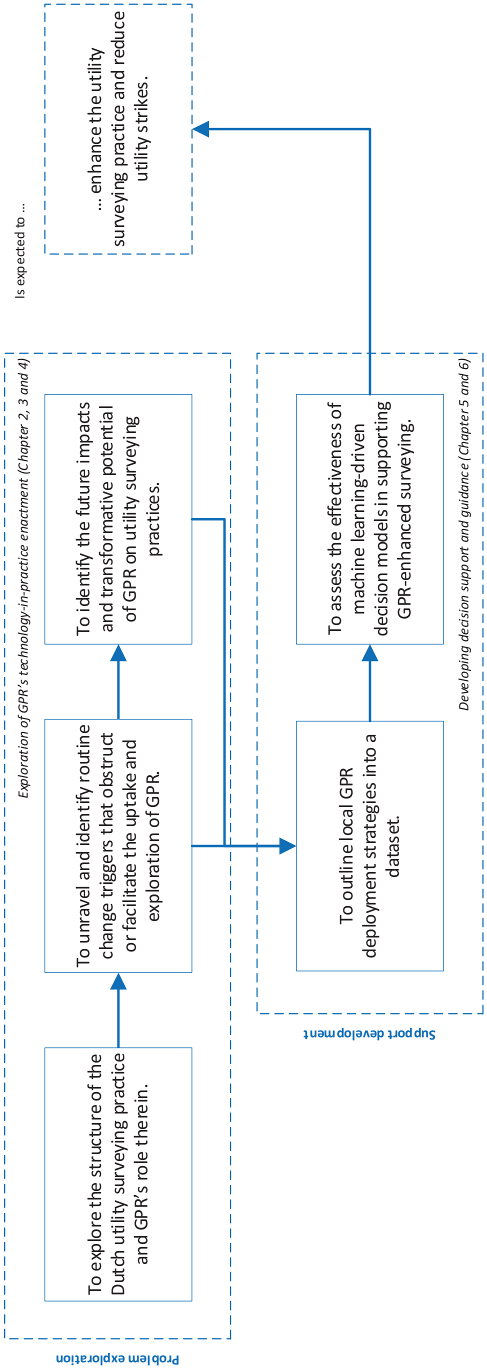


Figure 2. Interconnections between the objectives of the dissertation.

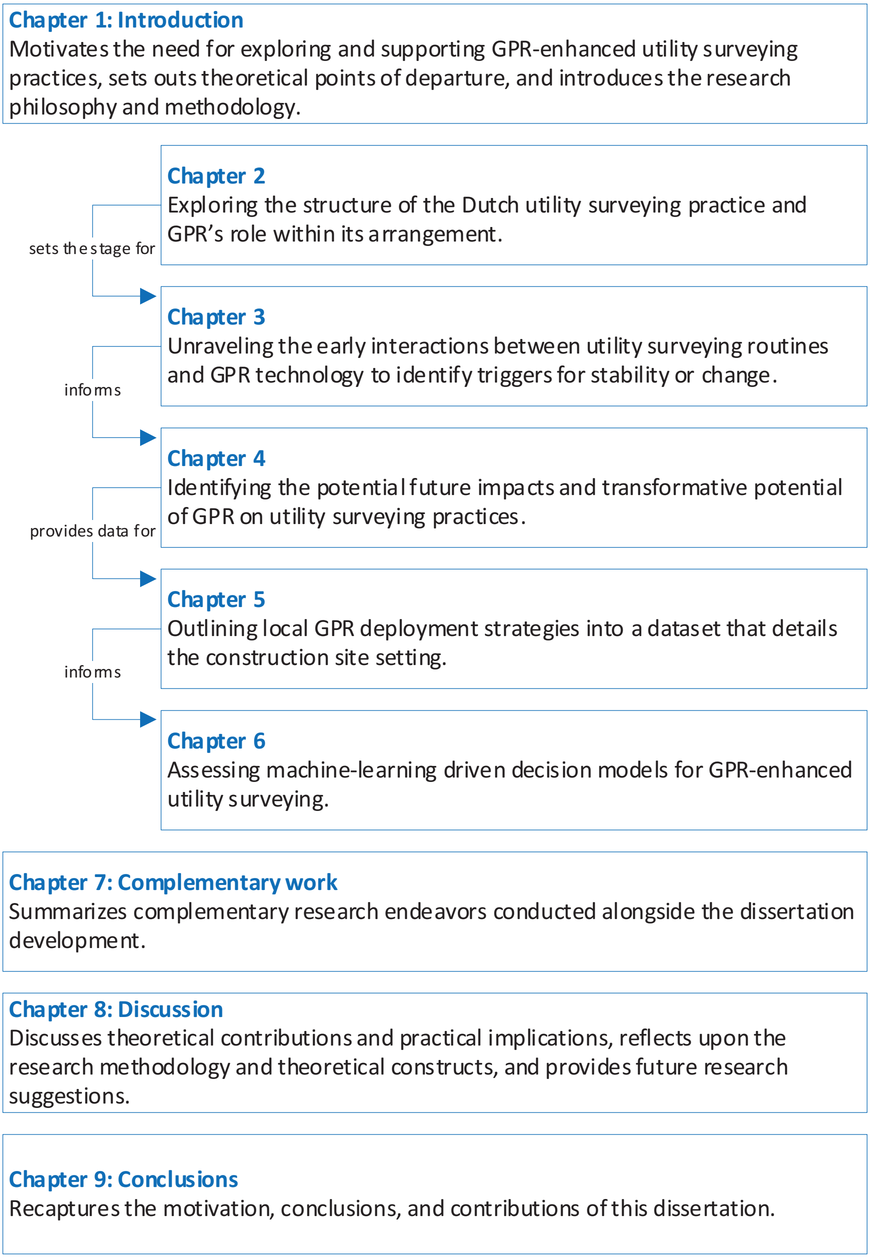
To define the objectives, the local use dynamics of GPR were unraveled using the technology-in-practice perspective (Chapters 3 and 4). From this perspective, I introduced GPR to thirteen construction sites across the Netherlands and collaborated with construction practitioners on 125 surveying activities. During this process, I either closely observed construction practitioners conducting surveying activities (such as digging trial trenches and consulting utility maps) or actively assisted them using the GPR technology. These interventions yielded valuable socio-technical insights into GPR's impacts and contributions to surveying practitioners. Together with these practitioners, I identified the most effective GPR deployment strategies at each local site that I visited. These strategies formed the foundational basis for developing the decision models.

To design and develop the decision models, I compiled a dataset that outlined the GPR deployment strategies by detailing each construction site setting (Chapter 5). This setting was described through its construction, geophysical, infrastructural, and technical features. Using this dataset as input, I developed both expert-based and generalized machine learning decision models for GPR-enhanced utility surveying. Following this process, I demonstrated the performance of each decision model developed by conducting experiments using a validation subset of the dataset (Chapter 6). This involved an analysis using quantitative metrics.

The same metrics were then used to evaluate each model's performance by comparing their outcomes against decisions made by utility surveying and GPR experts (Chapter 6). I organized an expert workshop where utility surveying scenarios were simulated to gather these experts' decisions. For these scenarios, experts were tasked with determining the optimal strategies for deploying GPR, addressing when, where, and how to use the technology effectively. This evaluation process facilitated further insights into each model's performance, ultimately aiding in selecting the most effective model for GPR-enhanced utility surveying.

1.6. Dissertation outline

Chapters 2 to 4 explore the problem context by clarifying the structure of the Dutch utility surveying practice and describe the GPR's technology-in-practice enactment through the theoretical lenses of routine dynamics concept and CHAT. Chapters 5 and 6 describe the compilation of a dataset and the development, validation, and evaluation of machine learning-driven decision models. Chapter 7 offers insight into complementary research endeavors conducted alongside the dissertation development. While the work in this chapter does not formally contribute to the primary research objective, it offers complementary perspectives on the contextual landscape within which this dissertation was undertaken. Chapters 8 and 9 finalize this dissertation by outlining its main theoretical contributions and practical implications, reflecting on the chosen research methodology and theoretical constructs, providing recommendations for future research, and outlining its main conclusions and outlook. Figure 3 presents this dissertation's outline.



Chapter 1: Introduction
Motivates the need for exploring and supporting GPR-enhanced utility surveying practices, sets outs theoretical points of departure, and introduces the research philosophy and methodology.

Chapter 2
Exploring the structure of the Dutch utility surveying practice and GPR's role within its arrangement.

Chapter 3
Unraveling the early interactions between utility surveying routines and GPR technology to identify triggers for stability or change.

Chapter 4
Identifying the potential future impacts and transformative potential of GPR on utility surveying practices.

Chapter 5
Outlining local GPR deployment strategies into a dataset that details the construction site setting.

Chapter 6
Assessing machine-learning driven decision models for GPR-enhanced utility surveying.

Chapter 7: Complementary work
Summarizes complementary research endeavors conducted alongside the dissertation development.

Chapter 8: Discussion
Discusses theoretical contributions and practical implications, reflects upon the research methodology and theoretical constructs, and provides future research suggestions.

Chapter 9: Conclusions
Recaptures the motivation, conclusions, and contributions of this dissertation.

Figure 3. The outline of this dissertation.

Chapter 2

exploring the structure of the Dutch utility surveying practice and GPR’s role therein

Mutual learning: A comparison between the Dutch and international utility surveying practices

Abstract

The collection and depiction of comprehensive and accurate information about subsurface utilities' locations and attributes – also referred to as utility surveying – has been a priority in the planning, design, and monitoring of construction projects for many years. Where internationally comparable utility surveying standards have been established (e.g., the British PAS 128, the American ASCE 38-02, the Australian AS 5488, and the Malaysian Standard Guideline for Underground Utility Mapping), this has not occurred in the Netherlands. Given the lack of a utility surveying standard, this study examines how the Dutch utility surveying practice is arranged, specifically looking at the localization of utilities prior to excavation works. Our findings show that the Netherlands primarily benefits from utility plans, verified through trial trenches, while seemingly neglecting the commissioning of geophysical methods. This practice mainly originates from the availability of a regulated central utility data-exchange platform and the obligation by law to precisely determine the location of utilities prior to excavation. After qualitatively comparing the Dutch utility surveying practice with the practices as outlined by the international utility surveying standards, we argue that two fundamental differences may provide lessons for both the Dutch and international surveying practices. Specifically, Dutch practice may learn from international practices that geophysical detection methods provide a complementary means to reduce excavation risk besides utility plans and trial trenches, whereas the international context, in turn, may learn that having a regulated central utility data-exchange platform helps to enhance the availability of utility plans.

Keywords

Utility surveying, trial trenches, geophysics, detection methods, practice.

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2.1. Introduction

The complexity of the unseen networks of subsurface utilities continues to grow as a result of urban growth, the development of new communication technologies (Jaw & Hashim, 2013), and the installation of new sustainable pipeline networks as a result of the energy transition (Kern & Smith, 2008). At the same time, today's society heavily relies on these networks' responsibility to transport water, gas, electricity, telecommunication, sewage, heating, and other services (Costello et al., 2007; Jaw & Hashim, 2013).

New construction, maintenance, and remediation projects often include works with or near subsurface utilities. In support of the planning, design, and monitoring of these works, utility owners, contractors, engineers, and decision-makers require accurate and comprehensive information about the utilities' locations and attributes (Chapman et al., 2007; Jaw & Hashim, 2013). This information typically is used to create maps of new utilities and to verify the locations and attributes of existing utilities. The verification of existing utilities is, thereby, usually conducted to verify design spaces or mitigate excavation risk.

Yet, the collection and depiction of utility information – also referred to as utility surveying – is widely regarded as a highly challenging task (Kraus et al., 2012). Information within utility plans – especially in the case of aging utility networks – is often inaccurate, incomplete, out of date, or even lacking (Costello et al., 2007; Metje et al., 2007). Moreover, the location of the utilities is typically only registered in two dimensions, lacking depth (Metje et al., 2007). Altogether, this means the information captured within utility plans regularly does not reflect the as-built situation. Therefore, practice is encouraged to complement the information acquired from utility plans through the employment of additional utility surveying methods. Examples of such methods include geophysical detection methods (e.g., ground penetrating radar (GPR), electromagnetic locator (EML)) and exposure of utilities by physically digging a trial trench (also referred to as trial holes, test holes, and potholing).

Internationally, no uniformly agreed-upon utility surveying practice is adopted. Therefore, as a result of different institutional settings of countries (e.g., legislation, ownership of utility networks, ownership of utility data, and responsibilities and liabilities within excavation works), various utility surveying practices emerged, on its turn potentially leading to different insights. In this study, we define utility surveying practice as the set of activities performed to detect and localize utilities. The next section elaborates on various utility surveying practices as outlined by international standards.

2.2. Background and related literature

Having accurate and comprehensive information about the utilities' locations and attributes has been a priority in the planning, design, and monitoring of construction projects for many years (Chapman et al., 2007). Although the need for such information has not led to an internationally uniformly agreed-upon utility surveying practice, authorities such as the British Institution of Civil Engineers (ICE) (2014), the American Society of Civil Engineers (ASCE) (2002), the Australian Standards (AS) (2013) and the Malaysian National Committee for Mapping and Spatial Data (2006) provide comparable utility surveying standards on a national level. Respectively, these include the PAS 128, ASCE 38-02, AS 5488, and Standard Guideline for Underground Utility Mapping. The standards set out provisions for the detection and verification of active, abandoned, redundant, or unknown subsurface utilities and their associated appurtenances (e.g., manholes).

Generally speaking, survey results of above-ground surveying methods such as geophysical detection methods undoubtedly yield larger uncertainty than survey results through utility exposure. To this end, the PAS 128, ASCE 38-02, AS 5488, and Standard Guideline for Underground Utility Mapping distinguish between four utility information quality levels: A, B, C, and D. These quality levels differentiate between the type of utility survey carried out (see Figure 4).

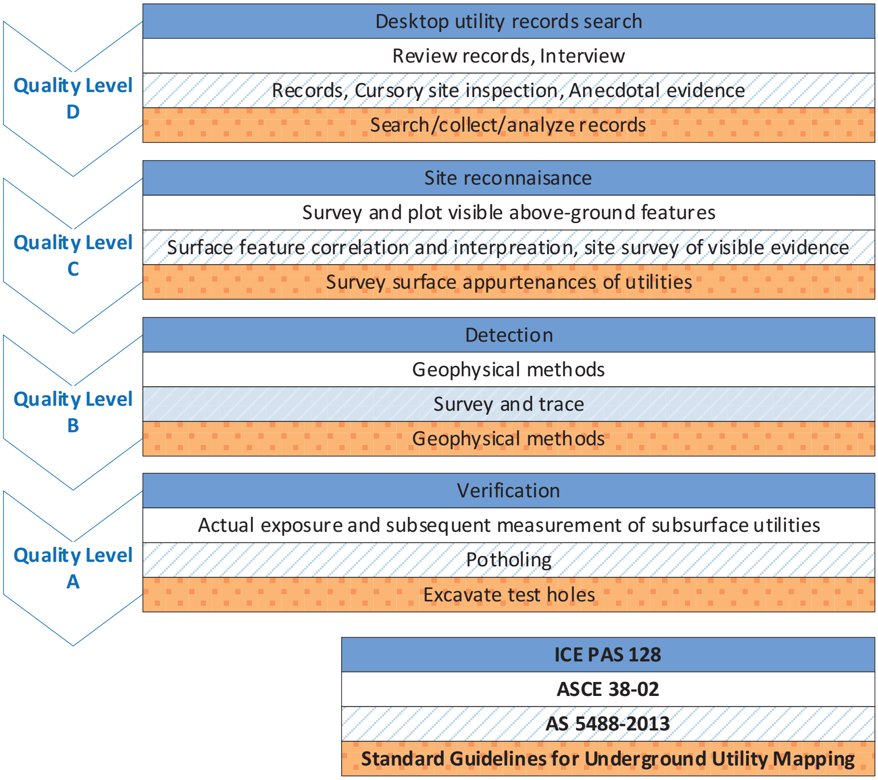

Figure 4. Utility data quality levels and corresponding surveying methods (adapted from Lai et al. 2018).

Quality level A involves the actual exposure of utilities – also called verification – thereby allowing for visual inspection and measurement of the utilities' accurate location and relevant attributes. Quality level B concerns the employment of geophysical methods to detect and identify utilities. The PAS 128 also provides a further subdivision of quality levels within quality level B, relating to the use of single or multiple geophysical detection methods and whether post-processing of the acquainted data is included. We refer the reader to the PAS 128 itself for further explanation of these quality levels. Quality level C relies on the identification of surface-level utility appurtenances (e.g., manholes, valves, hydrants) that support the existence of subsurface utilities. Quality level D refers to the search and review of utility plans.

The confidence in the accuracy of the surveying results – and thus utility information – gradually increases from level D to A. This means the results acquired from utility plans (quality level D) are perceived as least accurate, as opposed to the results acquired from verification through utility exposure (quality level A), which are perceived as most accurate. The quality levels, thereby, provide clients with a quality assurance measure, allowing them to select the expected quality level of utility information upfront of the utility surveying process. From now on in this study, we will refer to this practice as the 'international utility surveying model'.

Whereas the UK (PAS 128), USA (ASCE 38-02), Australia (AS 5488-2013), and Malaysia (Standard Guideline for Underground Utility Mapping) all have established comparable utility surveying standards, this has not occurred in the Netherlands. Despite the lack of a standard, the Netherlands implemented elements of the international utility surveying model into legislation and utility surveying practices. These elements primarily relate to the localization of utilities before excavation works to mitigate excavation risk. Other elements of the international utility surveying model, however, are less developed in the Netherlands.

To this end, this study examines how, via legislation and utility surveying practices, the Dutch utility surveying practice is arranged, specifically looking at the localization of utilities prior to excavation works. We systematically and qualitatively compare this perceived Dutch utility surveying practice with the international utility surveying model to identify differences and best practices. We explain the methodology followed in this study to achieve the latter in the next section.

2.3. Methodology

Differences between utility surveying practices, as well as their implications, have received limited attention in the literature so far. Therefore, we considered an exploratory research approach most appropriate. In specific, to gain insights on the topic, we conducted a qualitative comparative case study (Yin, 2018).

To explore the Dutch utility surveying practice, we selected the case 'the Dutch utility sector.' We studied Dutch legislation – i.e., a law and directive related to the localization of subsurface utilities prior to excavation works – and explored how this translated into action by assessing a work plan of a utility-related construction project, together with observing an actual utility surveying project in practice. First, the studied law (so-called WIBON, translated as the law on information exchange of surface and subsurface utility networks) dictates the obligations and responsibilities of organizations within an excavation work to minimize the risk of damaging utilities, while the directive (so-called CROW 500) sets out provisions for careful excavation to achieve the latter. Second, the work plan studied explicates the utility surveying activities planned for the design and installation of new gas pipes – including the removal of old gas pipes – in a rural environment. Third, the utility surveying work practice concerned the localization of utilities in an urban area. During the observation, we chose to keep a distanced role to minimize our interference on the surveying process.

The use of all three data sources (i.e., triangulation) allowed us to develop an understanding of the set of activities performed in the Dutch utility surveying sector from both the as-prescribed and as-performed perspectives. In analyzing these, we tried to identify the dominant established surveying methods that were used more frequently and tried to get first insight into the motivation for this.

We used the international utility surveying model (Figure 4) as a conceptual framework to analyze how the Dutch legislation, work plan and observed utility surveying practice compared to the former. Specifically, we qualitatively reflected the Dutch utility surveying activities and methods as found within the three data sources against the utility surveying methods as depicted in the utility surveying quality levels A, B, C, and D.

2.4. Results

In the Netherlands, legislation explicates the obligations and responsibilities of the related organizations within an excavation work. By law (WIBON), excavation contractors and their clients are imposed to a duty of care regarding excavation. As part of this duty of care, it is made compulsory for those planning to excavate to notify authorities of their excavation work upfront. This notification takes place through a regulated central utility-data exchange platform (Figure 5) and is conducted to check for subsurface utilities at the excavation site. Subsequently, the excavation notification is passed through to utility owners with utilities present at the excavation site. These utility owners are then obligated to send their utility plans (in vector format) to the central utility data-exchange platform within one working day. Utility plans should at least include the utilities' horizontal location, whereas its vertical location and typical attribute information like diameter and material are optional. Concerning the horizontal location, only a deviancy of one meter is allowed. Once all utility owners have sent their utility plans to the central platform, the excavation contractor receives this information package digitally.

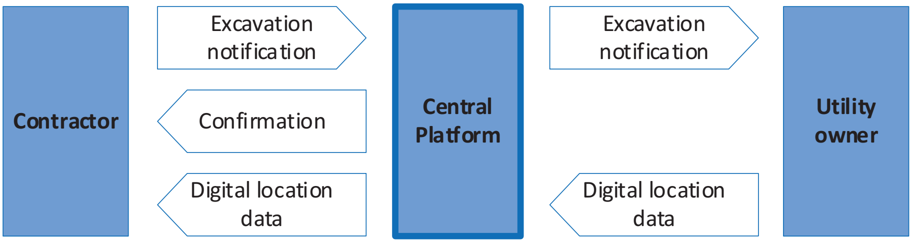

Figure 5. Dutch central utility data-exchange platform.

Besides, the duty of care specifies that a 'precise' determination of the location of utilities prior to excavation works is required. Given this duty of care, those who cause utility damage are, in the first instance, held liable. The latter typically also holds up in case incomplete and inaccurate utility plans are provided by the utility owners. Notably, the law does not further elaborate on what precise would mean in practice.

A complementary directive (CROW 500) on careful excavation sets out provisions for those involved in excavation works. The directive distinguishes between six phases of an excavation work, being: initiative, research, design, work preparation, realization, and use. As part of the research phase, the directive suggests that a designer or contractor requests utility plans (through the central utility-data exchange platform) to allow for a first assessment of the excavation risk. This is called an orientation request. The locations of utilities as depicted within these plans are, thereby, referred to as the 'theoretical location'. The directive suggests that in the subsequent design phase, additional surveying methods should be employed to find the 'actual location' of the utilities to design risk mitigation measures. In the work preparation phase, the contractor should perform an 'excavation notification' to obtain updated utility plans. The directive briefly mentions site reconnaissance and identification of surface-level appurtenances as a means to get additional utility information in this phase. Updated maps will finally be used to develop risk mitigation measures and work instructions for the realization phase. Work instructions may include the specification of additional surveying measures.

The CROW directive dedicates a separate chapter to determining the 'actual location' of utilities onsite. Although the chapter lists types of geophysical detection methods, this is very brief, and it follows a much more elaborate explanation of the use of utility exposure methods like trial trenches. The directive provides little guidance on how to select and use the methods listed to conduct geophysical detection. On the contrary, the employment of trial trenches is explained via a six-step approach, starting with marking the place where trenches need to be dug and ending with suggestions on how to record the findings. Altogether, we found that the directive focuses primarily on the use of utility plans and subsequent verification through trial trench solutions as a means to localize utilities.

Second, findings from the work plan analysis are as follows. The work plan of a utility-related construction project explicated the utility surveying activities planned for designing and installing new gas pipes (ranging from 100 to 300 mm in diameter) – including removing old gas pipes – in a rural area. The work plan specifies that utility plans (obtained through the Dutch central utility data-exchange platform) were used to predefine the surveying locations. In total, seventeen locations were chosen and outlined on a map. These surveying locations primarily included the connection points for the installation of the new gas pipes. The work plan specifies the use of trial trenches to verify these locations. The surveying locations are, thereby, verified on so-called 'verification points'. The verification points include topographic situation, ground level, presence and location of (unknown) appurtenances, and presence and location of subsurface infrastructure. Surveyors indicate this survey point using x, y, and z coordinates, preferably using GPS positioning. The plan also defined that specific properties, such as coating type, wall thickness, diameter, and slope of the gas pipes, had to be defined by visual inspection after exposure of the utilities.

In a separate chapter, the work plan provides guidance on how to conduct the trial trench survey. This chapter explains in rather general terms whether trenches should be dug manually or mechanically, how to deal with the excavated soil, and how to compact the soil after covering the trench. For one surveying location, the plan suggests the use of dewatering before digging the trench. Surveyors record the trenches' content with pictures and completion of a checklist. The plan did not refer to site reconnaissance or geophysical detection methods.

Third, we observed how surveyors onsite localized existing subsurface utilities to determine the available free underground space. This was required to define possible room for the installation of new telecom lines. The surveyor retrieved utility plans using an orientation request via the Dutch central utility data-exchange platform. He also used visual observation to identify surface-level appurtenances. The foreman explained that he decided onsite where he would dig trial trenches. Examples of cues that influenced the decision to dig trenches were distances from an electrical box, and the expected location of a bend in the route of a cable. Subsequently, the surveyor dug two trenches manually and recorded its content with pictures. He did not measure the location of the utilities. The foreman explained that he did not employ geophysical methods like GPR. The main reasons for this were that (1) he lacked experience and knowledge about the method, and (2) he previously had disappointing experiences with the method as a result of not being able to detect what he was looking for. The surveyor also explained that he uses EML methods (i.e., 'cat and genny') in other projects. Table 1 summarizes the practices studied in the Netherlands and allocates them to the utility surveying quality levels A, B, C, and D of Figure 4. We discuss our findings in the next section.

Table 1. Comparison between Dutch and international surveying practice.

International utility surveying model		**Studied Dutch utility surveying cases**
Quality level D	Desktop search and review of utility plans	Mandatory exchange of utility plans through the central utility data-exchange platform; Localization of utilities through utility plans provides a 'theoretical location'; Allowed deviancy of one meter in the horizontal position of utility plans; the vertical position is typically not included.
Quality level C	Identification of surface-level appurtenances that support the existence of utilities	Elaborated in CROW directive as part of the excavation works preparation; Identification of surface-level objects in observed practice to determine utility surveying locations.
Quality level B	Employment of geophysical detection methods	Seemingly marginalized in legislation (WIBON) and directive (CROW); Limited reference to/use of geophysical detection methods in studied work plan and practice.
Quality level A	Exposure of utilities for visual inspection and measuring	Dominant reference to/use of trial trenches in CROW directive and studied work plan; Verification of utility plans and locating of utilities by physically dug trial trenches in work plan and practice.

2.5. Discussion

As a result of the growing complexity and criticality of our subsurface utilities (Jaw & Hashim, 2013; Kern & Smith, 2008), surveying the latter has become increasingly challenging (Kraus et al., 2012). It is, therefore, surprising that the observed Dutch utility surveying practice focuses on a limited set of quality levels (see Table 1) and pays little attention to the employment of geophysical detection methods. One reason for this may be that its potential equivalent to quality level B – i.e., the central utility-data exchange platform – is well developed. Having a guaranteed availability of utility plans potentially seems to reduce the perceived need for surveyors to employ geophysical methods.

Although geophysical detection methods do not guarantee a complete and accurate detection of all buried utilities, they can help to obtain a larger amount of information about the underground when used in addition to local trial trenches and utility plans. Examples from literature (e.g., Chapman et al. 2007; Hao et al. 2012; Lester and Bernold 2007; Metje et al. 2007) already have demonstrated how geophysical detection methods could be employed to support the former.

The exchange of utility plans is obligated in the Netherlands, while the international context does not mandate this. The absence of a law in other countries leaves it much more open to utility owners to decide how they share information. Network owners may not be willing to share utility plans if they fear the national security or loss of competitive advantages (Kraus et al., 2012). Therefore, the availability of utility plans for a given construction site in the international context is not always guaranteed.

From the above, we draw the preliminary conclusion that the international context seems to benefit more from geophysical detection methods as a utility surveying method (quality level B) since these countries do not have the certainty of a utility-data exchange platform (quality level D). Nevertheless, we noted during this study that the United Kingdom has ambitions to create a National Underground Assets Register (NUAR) – including the London Underground Assets Register (LUAR) pilot. It would be relevant for future work to explore how this is going to influence the perceived need for geophysical detection methods.

We finally reflect on the Dutch context. It seems that the Dutch practitioners' motivation for not employing geophysical methods is in line with previous studies by, for example, Kraus (2012) and Lai et al. (2018). Lacking experience and knowledge by practice especially seem a limiting factor for the uptake of more 'sophisticated' geophysical detection methods like GPR. Lai et al. (2018), therefore, argue that more trained personnel is required to work with such detection methods. Consecutive research efforts should, hence, elaborate on what can and what cannot be expected from geophysical detection methods in utility surveying projects, paying specific attention to the information needs of a client. This would also help to shape more realistic expectations with practitioners about the methods' capabilities.

This study should be perceived as exploratory. Its limitation is primarily the amount of data collected and its consequent disability to generalize from this. In addition to the studied legislations and standards, we only studied one work plan and one utility surveying work practice within the Dutch utility sector. Besides, we studied international surveying practices only as outlined by the utility surveying standards. However, the data gave a good first impression of the utility surveying practices studied. Further studies can confirm our findings by extending our work with additional observations of work practices in the Dutch and international context.

Another limitation of this study is that we specifically studied the utility surveying practice with the purpose of localizing utilities prior to excavation works. However, utility surveying can also be carried out for mapping purposes only or just to verify the accuracy of utility plans. With a different purpose in mind, the utility surveying practice may require different insights, leading to a different arrangement of the surveying practice. Future studies may need to assess the effect of different utility surveying purposes on the arrangement of the utility surveying practice.

This study ultimately provides lessons for both the Dutch and international utility surveying practices. The Dutch utility surveying practice may learn from international practices that geophysical detection methods provide a complementary means to reduce excavation risk beside utility plans and trial trenches. The international context, in turn, may learn that having a regulated central utility-data exchange platform helps to enhance the availability of utility plans.

2.6. Conclusions

This study examined the Dutch utility surveying practice, specifically looking at the localization of utilities prior to excavation works, and qualitatively compared said practice with the international utility surveying practices as outlined within the British PAS 128, the American ASCE 38-02, the Australian AS 5488, and the Malaysian Standard Guideline for Underground Utility Mapping surveying standards. Our findings show that the Netherlands primarily benefits from utility plans (quality level D), verified through trial trenches (quality level A), while seemingly neglecting geophysical methods (quality level B). We argue that the observed Dutch surveying practice originates from the availability of a regulated central utility data-exchange platform and the legal obligation to precisely determine the location of utilities prior to excavation.

After qualitatively comparing the Dutch surveying practice with the international utility surveying model (see Table 1), we conclude that both include utility plans (quality level D), site reconnaissance (quality level C), geophysical detection methods (quality level B), and utility exposure (quality level A). Nevertheless, we argue that two fundamental differences in the way the surveying practices are manifested may include lessons for both the Dutch and international surveying practices. First, as opposed to the international surveying practice, the Netherlands largely seems to neglect the commissioning of geophysical detection methods. This is surprising given these methods' purpose and potential. Further studies could explore whether and how geophysical methods could be beneficial to the Dutch surveying context. Second, whereas the international context does include the search and review of utility plans, an alternative regulated way to do this is by having a central utility-data exchange platform like the Netherlands. Making the exchange of utility plans obligatory would vastly improve the availability of utility plans. Further studies may need to assess whether, within each national context, the concept of a central utility-data exchange platform is feasible.

Chapter 3

unraveling the early interactions between utility surveying routines and GPR technology

Change triggers in early innovation stages: How technology pilots enable routine reflection

Abstract

Many scholars have denounced innovation in construction as problematic. Existing work processes and routines may resist or even block the adoption of new technologies. Unraveling how new technology interferes with organizational processes could facilitate a more mindful innovation process. This study, therefore, conceptualizes how technology pilots influence early change of existing practices. Five utility localization projects were studied, in which ground penetrating radar (GPR) technology was introduced. The researchers observed existing practices onsite, demonstrated and moderated the use of GPR, and conducted semi-structured reflective interviews. Based on the concept of routine dynamics, selective and axial coding resulted in the identification of two types of mechanisms: (1) change triggers occurred when routines fell short and practitioners started favoring the GPR, and (2) stabilization occurred when routines proceeded as expected and shielded GPR from being considered. Objecting to linear innovation adoption, the findings contribute an empirical, conceptual model of early-stage innovation adoption dynamics. This model aids decision makers in timely identifying (1) whether routines are receptive to the uptake of new technologies, and (2) how new technologies may advance these routines. Additionally, this study demonstrates the merit of using practice-based studies to conceptualize in rich detail how innovation processes are shaped in situated construction contexts.

Keywords

Disruption, pilots, practice theory, routine dynamics, technology adoption.

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3.1. Introduction

Construction innovations may subtly change organizational processes already before organizations formally and consciously decide to adopt them. During this pre-adoption stage (Rogers, 2003), prospective users form an understanding and decide their favorability toward a technology. They shape expectations regarding the technology's future benefits to the organization (Lines & Reddy Vardireddy, 2017). The literature defines possible motivations of users toward the use of technological innovations (e.g., Choi et al. 2017; Davila Delgado et al. 2020; Nnaji et al. 2018, 2020; Pan and Pan 2019; Wang et al. 2020). Most of these factors followed from a questionnaire survey, and thus aimed to define generic causal models predicting professionals' usage and behavior. Although innovation scholars argue that technological adoption should be studied in a situated local context of use (Orlikowski, 2007), studies that explain how the identified factors emerge and shape dynamics during early innovation stages, are scarce. The literature would, therefore, benefit from closely conceptualized studies of practices that are confronted with construction innovations.

Practice theory provides a conceptual lens to do this by mapping the practical interactions between users' behavior and technological innovations (Feldman & Orlikowski, 2011). Within this stream of literature, the concept of routine dynamics specifically focuses on the level of daily activities (Feldman et al., 2019). Routine dynamics help to describe how interacting thoughts and actions of professionals stabilize or reshape existing construction practices during technology adoption (Becker, 2004; Feldman et al., 2016). Using this as a conceptual lens, the objective of this study is to develop an empirical conceptual model of early interactions between work processes of prospective users and new technology.

To achieve this, this study focused on a technology that currently enters the work processes of urban streetworks projects. At those sites, professionals need to assess the existing site conditions and verify the location of buried objects - such as cables and pipelines – before they start executing construction work. This is currently achieved through cut and cover excavation (Lai et al., 2018; Racz, 2017; Ter Huurne et al., 2020). The ground penetrating radar (GPR) technology gains popularity in the sector and could advance this existing localization routine (Lai et al., 2018). To study how the technology influences work processes in organizations that have no experience in using GPR, the researchers introduced it at five construction sites. Based on selective and axial coding of data from observations, demonstration and moderation of the technology, and reflective semi-structured interviews, two types of mechanisms were identified: those of change triggers and continued stability. This contributes to the literature with an empirical, conceptual model of early-stage dynamics during innovation processes and demonstrates the merit of using practice-based studies to conceptualize in rich detail how innovation processes are shaped in situated construction contexts.

The remainder of this paper is structured as follows. First, the interplay between technology adoption studies and routines is explained. Second, the research setting and methods that allowed the study of local practices in rich empirical detail are explicated. Next, the results are presented via analytic storylines and demonstrate mechanisms of routine change and stability. Finally, it is explained how the results smoothen the introduction of technology at post-adoption stages before outlining the limitations of this study and its possibilities for future research avenues.

3.2. Theoretical points of departure

Innovation adoption is:

> *"the process through which an individual (or other decision-making unit) passes from gaining initial knowledge of an innovation, to forming an attitude toward the innovation, to making a decision to adopt or reject, to implementation of the new idea, and to confirmation of this decision"* (Rogers, 2003).

During this process, innovations may change both organizational and operational practices (Sargent et al., 2012), regardless of the timing or relative degree of the newness of the technology (Rogers, 2003). This is because the prospective users of technology and the internal organizational and operational processes all may have to adapt to accommodate the new situation (Orlikowski, 2000). The literature, therefore, has previously attempted to develop an understanding of the factors that impact an individual's activities and cognitive processes. This helped clarify the individual's intent to use technology and create an understanding of the potential uptake process of technologies in the construction sector.

Classical frameworks presume that individual adoption of technology progresses linearly (Rankin & Luther, 2006). During the post-adoption stage (Rogers, 2003) of this process, formal and conscious decisions are made to implement the technology in an organization. Technology-in-use during implementation has been explored by many construction innovation studies. Such studies, for example, explore the impact of an adopted innovation on organizational goals and processes (Gurevich & Sacks, 2020), operational processes (Edmondson et al., 2001), and user acceptance (Lee & Yu, 2016). Although this is mostly studied at implementation stages, the interactions between technology and prospective users already can occur before, during pre-adoption stages (Rogers, 2003).

When professionals develop an early understanding and decide their favorability toward a technology at these stages, insights can be gained about how technology brings benefits to existing organizational and operational practices (Lines & Reddy Vardireddy, 2017). Further, post-adoption implementation is typically regarded as disruptive (ibid). The implementation of new technologies may enforce organizational and operational change (Orlikowski, 2000), causing opposing behavior among individuals (Heidenreich & Talke, 2020), triggering implementation failures (Klaus & Blanton, 2010). To stimulate more mindful innovation in construction, earlier assessments of the dynamics that may change when technologies are used would hence help to better understand in which situations technology can be used effectively, and where it cannot.

To date, popular models like the Innovation-Decision Process model (Rogers, 2003), the Theory of Planned Behavior (TPB) (Ajzen, 1991) and the Technology Acceptance Models (TAM) (Davis, 1986; Venkatesh & Bala, 2008) have provided ground for many studies that aimed to assess the motivation of users toward the use of technological innovations in the pre-adoption phase (e.g., Choi et al. 2017; Davila Delgado et al. 2020; Nnaji et al. 2018, 2020; Pan and Pan 2019; Wang et al. 2020). These models identify and define factors of motivation based on, for example, the attributes of perceived usefulness of the technology, the perceived ease of use of the technology, and the behavioral intention to use technology. Most of these factors followed from a questionnaire survey and aimed to define generic causal models predicting professionals' usage and behavior. As much as this is helpful as a first assessment of the merit of the technology, such factors do not depict mechanisms that are needed to describe the potential change processes at a micro-level when prospective users are confronted with a technology.

Current literature lacks a model that provides a detailed understanding of the interaction between technology and existing practices in the pre-adoption phase. This is needed to understand the dynamics that might take place when users are first confronted with a technology. Since the organizational context of construction innovations are complex and project-based (Gann & Salter, 2000), and therewith significantly different from most manufacturing innovations (Sarah, 1998), this study posits that construction innovations should be studied in a situated and local context of use instead (Orlikowski, 2007). Nevertheless, studies that explain how factors of motivation emerge and shape dynamics during early innovation stages in such contexts are scarce.

To address this knowledge gap, this study proposes to use closely contextualized studies of innovation in the situated and local contexts of practices. Literature advocates this can help to better understand the detailed, local dynamics that are at play when innovations confront the work practices of professionals (Orlikowski, 2000). Practice theory provides a conceptual lens to do this by focusing on the empirics of practice to elicit real-life dynamics constituted through the ongoing, everyday actions in practice (Feldman & Orlikowski, 2011).

Within practice theory, the concept of routine dynamics specifically focuses on daily activities (Feldman et al., 2019). Routines are repetitive, recognizable, and interdependent patterns of actions built around a mechanism of stability and change (Becker, 2004; Feldman et al., 2016). This dynamic called the generative mechanism of stability and change has been used in studies to better understand how organizational change processes take place (e.g., Bygballe et al., 2021; Danner-Schröder & Geiger, 2016; Turner & Rindova, 2012), and may, in turn, help to describe how interacting thoughts and actions of professionals stabilize or reshape existing construction practices during technology adoption (Becker, 2004; Feldman et al., 2016). By using routine dynamics as a conceptual lens, the objective of this study is to develop an empirical, conceptual model of early interactions between work processes of prospective users and new technology.

In particular, this study uses the generative mechanism of routines to map the so-called coexisting and recursively related performative and ostensive aspects (Feldman, 2000). Performative aspects of routines describe the actual actions (i.e., performances) “by specific people, at specific times, in specific places” (Pentland & Feldman, 2005). Ostensive aspects of routines describe the thoughts and patterns that people “use to guide, account for, and refer to the specific performances of the routine” (ibid). As such, the ostensive both guides performances, but is also created from the performances. Further, to understand how the performative and ostensive aspects are constituted, the conceptual framework of this study uses the attributes as used in the models of Davis (1986), Ajzen (1991) and Venkatesh and Bala (2008) to explicate professionals’ usage and behavior. Specifically, the experiences, expectations, and intent to use technology by professionals are mapped. Figure 6 presents the mechanisms used as the conceptual framework of the study.

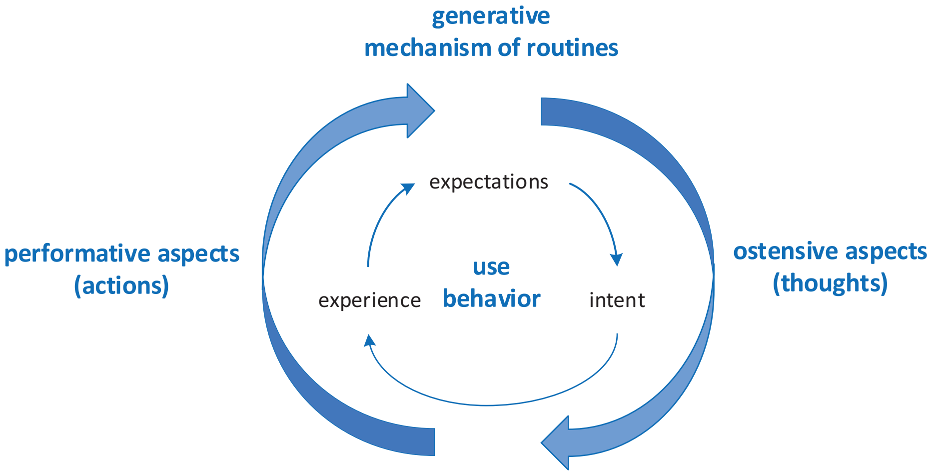

Figure 6. Conceptual theoretical framework adopted in the study.

3.3. Research method

This study adopts intervention research (Salkind, 2010) to qualitatively explore how the introduction of GPR on five construction sites influences the existing localization routine. The multiple cases were used to develop a broader understanding of this routine and to identify potential similarities and differences between the cases (Yin, 2018). Further, this study combines intervention research with grounded theory to streamline the case data toward theoretical interpretations, which are systematically gathered and processed through the research process (Corbin & Strauss, 2008).

This study explored the utility localization routines of five urban streetworks projects in the Dutch utility sector. Each case allowed for the exploration of GPR technology and studied different organizations. Organizations were considered eligible when they had considerable experience with the established utility localization routine but limited to no experience with GPR. This was verified before the pilots during an exploratory interview in which participants were questioned about their experience with the existing routine, their familiarity, and experience with GPR technology, and whether they expected GPR to advance the established routine. Participants included workers (performing the surveying activities), foremen and project managers (guiding the surveying process), and project owners (client of the surveying activity). To further expand the researchers' understanding of the projects, two-dimensional maps of the locations and types of utilities onsite, as well as work plans describing the planned surveying activities were collected. Table 2 summarizes the main characteristics of each case.

For each case, data were collected through three research phases and subsequently analyzed, as illustrated in Figure 7. The selected foremen, project managers, and project owners were part of the entire sequence of the three phases. The researchers only met the workers at the construction site during the second data collection phase, but questioned them onsite instead.

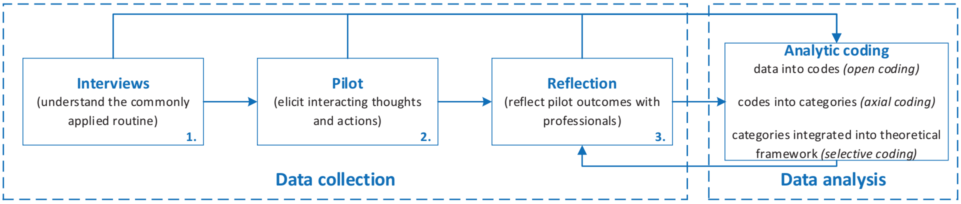

Figure 7. Main research steps.

Within the first phase, the researchers conducted semi-structured interviews of approximately one hour with the responsible foremen, project managers, and project owners. The professionals were questioned about how they commonly localize utilities onsite (the performative aspects) without the use of GPR.

Table 2. Description of the cases studied.

Case	Organization(s) involved	Project type	Construction stage	Planned construction activities	Localization goal
1	Utility owner. Contractor, specialized in utility location practice.	New installation.	Planning.	Installation of new city heating pipelines, including supply and return lines.	Verify locations of utilities on existing maps; Determine how new heating lines cross the existing utilities; Determine the free space for the new heating lines.
2	Contractor, specialized in utility location practice.	New installation.	Planning.	Installation of three new medium voltage electricity lines.	Verify locations of utilities on existing maps; Determine the free space for the new electricity lines.
3	Utility owner. Contractor, specialized in utility location practice.	Rehabilitation.	Planning.	Replacement of old asbestos cement freshwater, medium voltage electricity, sprinkler, low-pressure asbestos cement gas, heating, cooling, rainwater sewer and wastewater sewer lines.	Verify locations of utilities on existing maps; Find the asbestos cement lines that had to be replaced; Determine the free space for the new utility lines.
4	Utility owner. Contractor, specialized in utility location practice.	Rehabilitation.	Planning.	Replacement and repositioning of old freshwater line.	Verify locations of utilities on existing maps; Find the old water line that had to be removed; Determine the free space for the new water line.
5	Contractor, specialized in utility location practice.	Rehabilitation.	Planning.	Replacement of old freshwater lines.	Verify locations of utilities on existing maps; Find the old water line that had to be replaced; Determine the free space for the new electricity lines.

Additionally, the participants were questioned about their prior experiences with, and thoughts of (the ostensive aspects) the existing localization routines. The first phase further expanded the researchers' understanding of the participants starting beliefs and behavior.

Within the second phase, the researchers supported pilots that took, depending on the size of the construction site, one or two full days. The pilots took place in parallel to existing utility localization routines, which meant that professionals onsite executed their normal routine, but were also confronted with GPR while the researchers executed GPR measurements at the same site. This familiarized professionals with the technology in a minimally intrusive way and without a deliberate purpose to influence the professionals' ongoing routines. Although the researchers did not initiate action, professionals observed how the technology was used and consequently gained the chance to assess how this could impact their existing routines. To this end, a moderate participation stance (DeWalt & DeWalt, 2011) was adopted since the researcher did not only passively observe the actions in practice but also assisted professionals in case of a request to use GPR in their routines, given their unfamiliarity with GPR and its complex use. To capture data about the actions and thoughts of the professional during the pilot, the first author of this article took notes, pictures, and occasional videos of the site. Additionally, unstructured and spontaneous dialogues with the professionals on the research site helped elicit the reasoning behind the choices that were made by the professionals in practice.

Within the third data collection phase, reflective semi-structured interviews of approximately one to two hours were conducted with the professionals to discuss their pilot experiences, expectations, and use behavior. Namely, it was discussed how the prior thoughts of the existing routine were impacted, how the pilot experiences with GPR were perceived, and how these experiences initiated changing thoughts and beliefs about the role of GPR in the current routines. The interviews, therewith, helped assess whether the pilot had set routines into change and what might have caused that change.

To analyze the data, the researchers used the analytic coding procedures of Corbin and Strauss (2008). First, open coding was applied to code the interview and field note data line-by-line to categorize the data into codes. Codes were, for example, ‘experiences with GPR’ and ‘findings of localization efforts.’ Second, these codes were linked and grouped into broader categories and subcategories via axial coding to identify the logic behind how and why technology pilots initiate the stabilization or change of a routine. Categories identified were, for example, ‘disruptions in the routine’ and ‘GPR use behavior.’ Finally, the researchers integrated the categories and subcategories into the ostensive-performative cycle via selective coding and expanded the theoretical model of Figure 6 by including the mechanism that led to stability or change of the existing utility localization routine. The results are presented via an analytic storyline that explains the sequence of the professionals' actions, reactions, and interactions (Saldaña, 2013). Within this storyline, the key events within the mechanisms of stability and change are highlighted and described.

3.4. Results

The five cases demonstrated the existence of two different types of mechanisms: one of routine changing, and the other of routine stabilizing. Although they were observed in multiple cases, the results show one case as illustrative evidence for this mechanism and subsequently explain in brief how this was observed in other cases.

3.4.1. Mechanism 1: Routine change

Events observed during the pilots showed how, through the confrontation with technology, professionals decided to use GPR and alter their routines consequently. This mechanism demonstrates the flexibility in routines to adapt to new technology introduced in the practical context of work, and was, among others observed in Case 3. Case 3 comprised a rehabilitation project at a university campus in which a series of utility services were replaced with new ones because of growing service demand, the deterioration of old utility lines, and the presence of harmful asbestos cement water and gas lines. Further information on the case can be found in Table 1.

During the interview that was held before the pilot, the project manager explained the intent behind the established localization routine: *"You want to know what is in the ground. Is the KLIC [i.e., the existing utility maps] correct? With trial trenches [i.e., cut and cover excavation] you see exactly what is there."* Trial trenches are a commonly applied utility localization method in the Dutch localization routine to verify the location of the utilities on the utility KLIC maps. The project manager explained his and the organizations' a priori experiences with and expectations for GPR technology: *"We have looked at the subsurface with radar in the past, but the question always remained: have you found everything [i.e., all subsurface utilities]? What do you get for your money? There is always a need for a trial trench [i.e., cut and cover excavation]. The radar cannot give you the same level of certainty. The radar is simply not a normal product."* With 'certainty' referring to the locational accuracy of the utility lines in the x, y, and z coordinates and 'normal' to GPR not being considered part of the established utility localization routine yet, the project manager expected GPR technology in the practical context of work to be inferior compared to the existing routine, disincentivizing the intent to use the technology at the construction site.

During the next data collection, a two-day pilot took place in which the researchers used GPR at the construction site. Four professionals were present: the project manager, the foreman, and two workers. At the start, their working activities comprised the established trial trenching routine: the professionals consulted the utility maps, examined which subsurface utilities were to be reconstructed, and then decided where on the site those utilities had to be exposed by manual and mechanic excavation. Subsequently, the x, y, and z location, type, material, and diameter of the localized utilities were noted by the foreman. Locations of utilities were measured with both tape measures and professional GPS-surveying equipment. Also, pictures of the exposed utilities were taken. During these early stages, no technological intervention took place, and no discernible changes to traditional work practices were observed.

The first key event during the pilot occurred when both the foreman of the contractor and the project manager debated about uncertainties in the location data of medium voltage electricity cables. They wanted to expose these cables using trial trenches, but the shortcoming of the map used as a basis for the existing routine triggered a discussion about utility maps and their accuracy. They concluded that in general KLIC-maps are known to be not completely reliable and did not yet want to start excavation before they reduced the uncertainty they had regarding the chosen trial trench location. They stated: *"The KLIC [i.e., utility maps] always has some sort of deviation. I seem to remember that they [i.e., the medium voltage electricity cables] run differently than drawn on the map."* To reassure that the electricity cables were found, the project manager then approached the researcher and asked: *"Although I know that the cables and pipes are here somewhere, I am not exactly certain about the location of the medium voltage cables ... Could you look here [with GPR technology] to see whether the trial trench [i.e., cut and cover excavation] is set at the right location, or do we maybe need to dig further? What can you find here?"*

The observed event demonstrates that the professionals started to assess the merit of the GPR technology in the local practice after they were confronted with a shortcoming of their existing routines. This routine reflection led, in turn, to the intent to use GPR and shaped new use behavior. In this situation, the GPR technology was able to confirm that professionals chose the correct location for their trial trench.

A related second key event was that the use of the GPR led to the detection of unregistered steel pipelines, of which both the foreman and project manager were not aware. Consequently, the foreman asked for the use of GPR at every successive location where trial trenches were planned. At that moment, the GPR technology became part of the sequence of actions performed. This disruption or expectation (i.e., the detection of unmapped pipelines) again leads to an assessment of the merit of GPR technology for the existing routines. Subsequently, this again led to new behavioral intent and new use behavior. Both the newly created thoughts and observed actions thus indicate routine change because of the pilot.

During Case 3, more examples were observed where new experiences shaped new expectations, leading to a new intent and use behavior. During one successive event, for example, one of the professionals asked the researcher to use GPR and support the routine as follows: *“Could you look at this location? We must find pipe protective casings here that cross the road. You should be able to find these with relative ease. They are quite big. Can you tell whether our trial trench [i.e., cut and cover excavation] is planned at the right location?”* Again, this request shows that the previous experiences with the technology seemingly shaped a favorable expectation about the merit of GPR technology. The request to support the utility localization with GPR further demonstrates a change of intention to use the technology.

The previous examples of how the technology pilot impacted the routine have been from the actual activities onsite. Case 3 also showed that the project manager envisioned that the technology had merit in successive cases. While thinking out loud, he told the researcher the following: *“Since the radar is here anyway, we could also go to … [another location] to scan there. We need to know the location of the cables and pipes in front of the … [name of a building] to update our archive and for when we start our construction activities there.”* This example shows that the new experience, induced by the disruptions and shortcomings of the existing routines, also triggered thoughts about new intents to use the technology. The changes in the localization routines, thus, seem to have transcended the single case studied, suggesting that a routine change might have been initiated. The new experiences further led to changed expectations about GPR, as explained by the project manager during the reflective semi-structured interviews after the pilots: *“My expectations about the radar have grown. In the past, we never worked like this [i.e., with GPR technology] and typically were not as directly involved during the localization of utilities … The radar supported us really well. We had to dig more as a result [i.e., of the unexpected finding of the unregistered pipes] but that helped us during our excavation activities.”*

As a result of unveiled disruptions and shortcomings in the routine, pilots thus may set routine reflection into motion and, therewith, may change routine user experiences, reshape future expectations, and trigger an intent to use the technology in successive activities, leading to early routine change. Pilot experiences and expectations may trigger a mechanism of routine change that is represented as the mechanism in Figure 8.

Similar routine changes were observed in other cases. In Case 5, for example, the disruption of the existing routine took place when a steel sewage pipe could not be found via the conventional method of a trial trench. The professionals found that the available utility maps were unreliable, and this led them to ask the researcher to scan the area with the GPR, to locate the ‘missing’ pipe: “*There must still be a pipe here, but we can’t find it yet [i.e., with cut and cover excavation]. We can check to see if it is located under the street if you can scan there?”* Here, the shortcoming of using a map to determine a trial trench location led to an assessment of the merit of GPR technology.

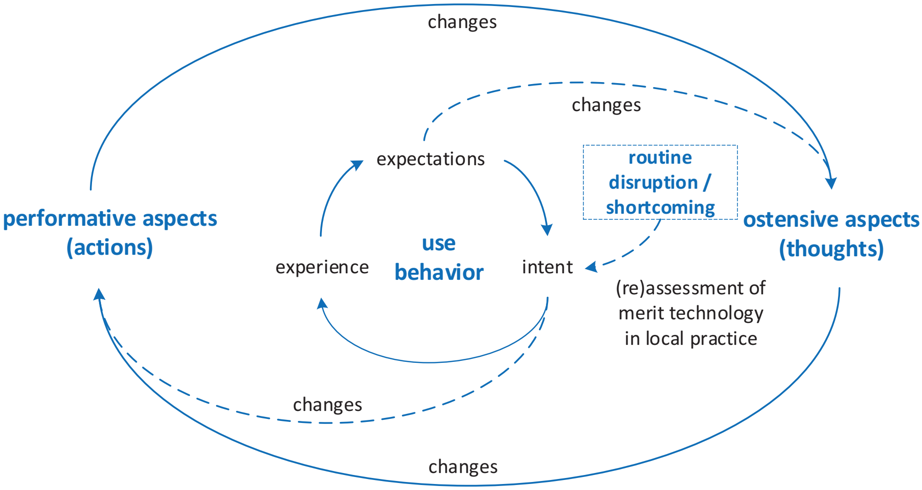

Figure 8. Routine changing mechanism.

The technology was assessed to overcome the faced shortcoming and allowed for exploration of the technology in the practical context of work. When the GPR technology proved to be capable of finding the missing pipe in Case 5, it shaped new expectations among the professionals about the merit of the technology. One of the workers approached the researcher and asked: *"If you find other deviances with the radar [i.e., in addition to the missing pipe], can you let us know? We still have to dig the test trenches [i.e., cut and cover excavation] on the other side of the street."* For the remainder of the project, GPR technology was used in successive activities to support the conventional utility localization practice by verifying the prior chosen trial trench locations onsite.

3.4.2. Mechanism 2: Routine stability

The other cases demonstrated that the functionality of existing routines, or put differently, the absence of routine disruptions or shortcomings, did not incentivize professionals to deviate from their existing routines. The routines remained stable, despite the availability of new technology on the construction site. This mechanism of routine stabilization demonstrates the inertia in routines to adapt to new technology. Stabilization was, for example, observed in Case 1. Case 1 comprised an installation project in the inner-city in which a new heating system was installed to provide a new apartment complex with central heating.

During the interview that was held before the pilot, the project manager revealed the existing thoughts about the technology. The manager explained the lack of experience with the GPR as follows: *"Low, very low. We haven't applied radar before, and actually, I only know it by name."* This meant the pilot would be the very first encounter of the project manager, as well as the other professionals present, with GPR technology. Additionally, the project manager explained the, and the organization’s a priori expectations for GPR technology: *“I expect that the radar will have a difficult time in a crowded area [i.e., many cables and pipes in the subsurface]. In a city environment where the subsurface is very crowded, I think it will be hard to identify cables and pipes on an individual level. Because we need to have precise information about everything that is here [i.e., the cables and pipes], I do not expect the radar to be reliable enough.”* To find the information required, the project manager expected the established localization routine to prevail over the alternative pilot GPR technology.

During the next data collection, a two-day pilot took place in which the researchers used a GPR at the construction site. Four professionals were present: the project manager, the foreman, and two workers. At the start, their working activities comprised the established trial trenching routine: the professionals consulted the utility maps, examined which subsurface utilities were to be found, and then decided where on the site utilities had to be exposed by manual and mechanic excavation. Subsequently, the x, y, and z location, type, and for most utilities also the material and diameter were noted by a subcontracted surveyor. While recording the location, pictures of the exposed utilities were taken by the crew. During these early stages, no technological intervention took place and no discernible changes to traditional work practices were observed.

The first key event during the pilot occurred when an electricity cable could not be found through excavation. The event delayed the ongoing localization activities since utilities had to be found before proceeding to the next planned trial trench location. To reassure that the missing cable would be found, one of the workers then approached the researcher and asked: *“You can find cables and pipes with that thing [i.e., GPR technology] right? Can you look where it [i.e., the missing cable] is?”* The observed event demonstrates that the professionals started to assess the merit of the GPR technology in their practice after they were confronted with a shortcoming – i.e., not being able to locate a cable using excavation - of their routines. This shortcoming led to the intent to assess and use technology. This first event introduced the professionals to the GPR technology, shaping new use behavior.

The GPR technology, however, did not find the missing electricity cable, despite scanning a broad area in which the cable was situated according to the utility maps. In the local context, the subsurface was very congested with many cables and pipes. The missing electricity cable had a relatively small diameter and was difficult to find amid this stack of utilities. This meant the local context did not lend itself well to GPR usage, resulting in the cable not being found. This demonstration of the GPR led to new experiences among the professionals. However, the assessment of the merit of the GPR technology was perceived as seemingly unfavorable: the use of GPR by the expert did not lead to a better evaluation of the whereabouts of the electricity cable compared to the existing routine. For further utility locating activities during this case, the professionals did not request the use of the GPR.

When reflecting on the merit of the technology after the pilot, the project manager explained that the GPR confirmed the prior expectations: *"Not as a replacement [i.e., for cut and cover excavation] in an area with many cables and pipes. The reason is that the radar cannot find cables and pipes on an individual level. You need to know whether you have found everything [i.e., all cables and pipes]."* Future adoption of GPR and change of the ongoing activities accordingly was not considered a viable alternative to (partially) replace the established localization routine.

Once again, through unveiled disruptions and shortcomings of the existing routine, pilots set routine reflection in motion and thus may create new user experiences. However, the initial success of the technology in overcoming the specific – locally identified – disruption or shortcoming of the existing routine determines in which way the initial experience reshapes expectations and triggers an intent to use the technology. The observed unfavorable experience with the piloted technology did not incentivize a behavioral intent to use the technology elsewhere. The routine kept stable. Figure 9 summarizes this mechanism in which pilot experiences and expectations trigger a mechanism of continued routine stability.

Similar routine stability was observed in Cases 2 and 4. In Case 2, none of the professionals approached the researcher to use GPR. Showing no signs of routine disruptions, shortcomings, or routine reflection, the existing utility localization routine proceeded without the use of GPR. The absence of the former thus led to continued routine stability despite the availability of new technology on the construction site.

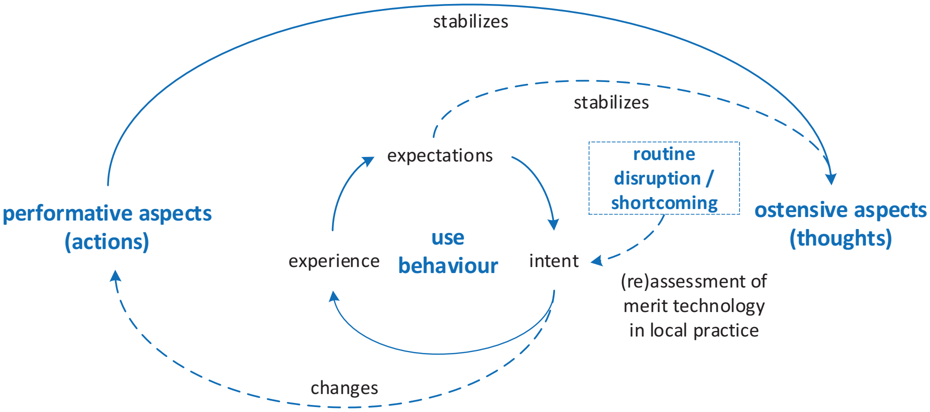

Figure 9. Routine stabilizing mechanism.

Further, in Case 4, the existing routine was disrupted when a public lighting cable could not be found via the conventional cut and cover excavation. The utility maps proved to be unreliable in providing the correct coordinates for the public lighting cable. To find the missing cable, one worker approached the researcher and asked: *"The public lighting cable should be here, between the streetlamps. Can you look with the radar? I guess the cable does not follow the straight path as shown on the KLIC [i.e., utility maps]."* In search of a solution to overcome the faced disruption, the professionals started to assess the merit of GPR technology and asked the researcher to scan the location. This allowed for the instantaneous exploration of the technology onsite. However, the use of the GPR did not lead to a better evaluation of the whereabouts of the missing cable compared to the existing routines. Like Case 1, the use of GPR in Case 4 led to a new experience among the locating professionals but arguably also to an unfavorable assessment of the merit of the GPR technology for the existing routines. For the further activities during the remainder of the pilot, the professionals did not approach the researcher again to use GPR, engaging in continued routine stability.

3.5. Discussion

This study used the lens of routine dynamics to develop an empirical conceptual model of early interactions between work processes of prospective users and new technology. This resulted in the following three contributions.

First, this study contributes to the construction innovation literature an explicated and empirically grounded conceptual model of routine change and stabilization mechanisms during technology pilots. Specifically, this model demonstrates that change triggers are crucial in initiating either routine change or routine stability. This aids decision-makers in timely identifying (1) whether routines are receptive to the uptake of new technologies and (2) how new technologies may advance these routines. The study, therewith, objects to the presumed linearity of innovation adoption theories (Rankin & Luther, 2006) and provides a first empirically rich understanding of the routine dynamics in early innovation stages to construction innovation literature.

The mechanism of routine change depicts how the emergence of change triggers incentivizes professionals to assess the merit of the technology instantly. Change triggers, either in the form of routine disruptions (events where existing routines lead to new results) or routine shortcomings (events where routines lead to deviating results), happen when existing routines fall short. As a solution to the failing routine (Feldman et al., 2016; Feldman & Pentland, 2003; Mitropoulos & Tatum, 1999), professionals enact an alternative-seeking behavior (Levitt & March, 1988). Findings demonstrate that the subsequent exploration of new technology creates new experiences, reshapes future expectations, and, in turn, may trigger an intent to use the technology in successive activities. This indicates an early routine change. The identification of this mechanism thus suggests that routines susceptible to change triggers are also receptive to the adoption of new technologies.

The other mechanism depicts how either the absence of change triggers or implementation failures leads to continued routine stability. Findings demonstrate that stabilization of routines occurred if the routines proceeded as expected. Despite having ready-to-use alternatives to the routine (i.e., the introduction of new technology) – offering opportunities for new routine directions as demonstrated both in this study and in recent routine literature (Kiwan & Lazaric, 2019) – this study and prior literature suggest that established experiences seemingly steer decision-making toward the existing routine (Betsch et al., 2001). This demonstrates an inertia to change that shields professionals from new actions and hampers the uptake of new technology (Pentland et al., 2012).

Further, even in case of change triggers, the initial success of the new technology as an alternative to the prevailing routine determines in which way the initial experience reshapes expectations and triggers an intent to use the technology. Findings indicate that unfavorable experiences of exploring the new technology hamper the further accumulation of experience with that routine, even when the new routine is considered superior (Levitt & March, 1988). This confirms that the likelihood that a new technology-enabled routine is used decreases when it is associated with failure in advancing the existing routine (Rogers, 2003). Such early unfavorable experiences may thus significantly hamper later innovation adoption stages.

This study adds to the context of innovation adoption processes that unveiling change triggers in early stages – such as the types of disruptions and shortcomings identified in this study – may initiate routine reflection and a subsequent exploration and uptake of new technologies in construction practices. This suggests that construction innovations should focus on those situations where the existing practices are susceptible to falling short. These situations are most likely to exhibit a dynamic in which new technologies could replace routines. Notwithstanding, even within this dynamic, contractual arrangements or specific project delivery methods (PDM) may significantly impact whether practices and their routines are truly receptive to the uptake of new technologies (Adriaanse et al., 2010).

Second, this study demonstrates the merit of the routine dynamics lens in practice-based innovation studies at pre-adoption stages. In the previous literature, routine dynamics were already used to better understand how organizational change processes take place (Bygballe et al., 2021; Danner-Schröder & Geiger, 2016; Turner & Rindova, 2012) but not specifically as a lens to study the micro-dynamics in innovation processes. The detailed and empirically rich descriptions gathered through the lens of the routine dynamics complement the individual behavioral change models of Davis (1986), Ajzen (1991), and Venkatesh (2008) that focus on an individual level but do not allow for a detailed analysis of performed practices and behavior. Instead, this study demonstrates that focusing on actions helps in disentangling complex organizational phenomena like technology adoption in routines (Feldman et al., 2019). However, while the use of technology is not necessarily unique, the use of technology-in-practice-based studies is always situated (Orlikowski, 2007). Scholars should thus proceed with caution in generalizing results from practice-based studies if these results are not demonstrated across a variety of local and situated contexts of use.

Additionally, since the adoption and use of technology, especially in the construction practice (Gann & Salter, 2000), is highly context-dependent, this study stresses the importance of the early engagement with technological innovations in a practical context of work to better understand the value and use of technology in its situated action in practice (Feldman et al., 2016; Orlikowski, 2000). By using routine dynamics, this study is a first example of how an empirically rich, local context of innovation can be studied to better understand how professionals' interacting thoughts and actions impacted the generative mechanism of performative and ostensive aspects and, in turn, technology use behavior.

Third, this study also has practical contributions. By identifying those conditions in which the technology is seemingly favorable for the prospective end-user, organizations might be able to describe what the value is that technology brings to existing operational processes. The advantage of a pilot – that is supported by technology experts – is that it brings an instantaneous opportunity for prospective end-users to freely explore technology as part of their ongoing routines. Since postadoption technology implementation is considered to be rather disruptive, enforcing organizational change (Lines & Reddy Vardireddy, 2017), provoking opposing behavior (Heidenreich & Talke, 2020), and potentially triggering implementation failures (Klaus & Blanton, 2010), this study postulates that the possibility to change routines in early adoption stages could stimulate an alignment between technology, its users and the practical context of work. This grounded understanding might eventually streamline adoption processes in practical contexts of construction toward more mindful and less disruptive implementations of new technologies.

Finally, this study offers recommendations and opportunities for further research. First, the chosen research approach provided limited insights into the thought processes of the individuals. For future research, the researchers recommend that scholars adopt an auto-ethnographic research approach, in which they use their personal experiences from the field to describe, analyze, and understand complex and often multi-layered cultural phenomena (Ellis et al., 2011). Rich descriptions of these experiences may help to further amass the thoughts processes of individuals during technological pilots, and therewith, understand its impact on routines better.

Second, it was not observed whether a sustained change of routines took place. Instead, this study claims whether and when the pilots initiated a mechanic of routine change or stabilization. Successive studies could observe the prospective users for a longer time frame to explore whether the routine change or stabilization was sustaining.

Third, the presence of the researcher as moderator of the pilot technology – which was indispensable given the lack of experience of practitioners with the technology – likely influenced how the professionals shaped their behavior. This is also known as the Hawthorne effect (Oswald et al., 2014). The presence in itself might have already triggered the attention of technology-savvy professionals, leading to an inquiry into its use in their routines. So, despite the attempt of the researchers to not voice their opinion and steer conversations about the value of the technology, it could not be avoided that practitioners were influenced by the researcher's presence. The researchers recommend that future studies consider this impact on professionals carefully.

Fourth, although the pilots evidently correlate to the identified mechanisms of stability and change, this does not prove causality even though this seems very likely. Future studies are, therefore, recommended to consider baseline cases as a benchmark against which the outcomes of the pilots can be assessed.

3.6. Conclusions

This study conceptualized how technology pilots influence early change of existing practices. Specifically, it was explored whether and how GPR technology influenced the generative mechanisms of stability and change of utility localization routines of five urban streetworks projects in the Dutch utility sector. Through a combination of interviews, observations and intervention research, findings demonstrate that new technology like GPR can initiate both mechanisms of routine change and routine stability. When prevailing routines fell short, this enabled professionals to reflect on the routine and assess the merit of the technology as an alternative solution. The subsequent exploration of the technology created new user experiences, reshaped future expectations, and triggered the use of technology in successive activities. This indicates the start of a potential routine change. Conversely, this study demonstrated that when routines proceeded as expected, the routine shielded professionals from the uptake of GPR.

The contributions of this study are as follows. First, it contributes to the construction innovation literature with an empirical, conceptual model of routine change and stabilization mechanisms when innovations enter a construction practice in the pre-adoption stages. Second, it demonstrates the merit of the theoretical lens of routine dynamics to conduct studies of situated local practices during innovation pilots at construction sites. This enhances the understanding of the implications of technology adoption and contributes to the existing literature an empirically rich study in the practical context of work. Third, to construction practice, the routine concept brings a meaningful way to better understand whether existing routines are susceptible to change, and therewith, receptive to new technologies. This grounded understanding might eventually streamline adoption processes in practical construction contexts.

Finally, this study offers opportunities and suggestions for further research. Scholars are recommended to adopt an approach such as auto-ethnography to further expand insights into the thought processes of individuals partaking in technology pilots; suggested to extend observations beyond the level of pilots toward other innovation adoption stages; urged to carefully consider the impact of the presence of the researcher on routine dynamic change in technology pilots; and advised to consider baseline cases against which the outcomes of pilots can be assessed.

Chapter 4

identifying the future impacts and transformative potential of GPR on utility surveying practices

Using formative interventions to study emerging technologies in construction practices: The case of the ground penetrating radar

Abstract

The potential impact of emerging technologies is challenging for construction management researchers to study, as these technologies have yet to become embedded in current organizational practices. Cultural-Historical Activity Theory (CHAT) offers a method called formative interventions that may assist in this challenge. However, existing formative intervention methods are not adequately tailored to the study of emerging technologies, necessitating a more immersive engagement of the researcher-interventionist. This article proposes a renewed participatory take on the role of the researcher-interventionist and outlines the actions that researchers can undertake to investigate the future impacts of emerging technology. Specifically, we describe the interventionist role through a study of utility detection activities in which we intervened with emerging ground penetrating radar (GPR) technology at twelve construction sites. We analyzed our role through an inductive coding approach using interviews and field visit data. Our findings reveal five interventionist action types for intervention studies with emerging technology. These include shaping conditions, exposing tensions, supporting problem resolution, operating tools, and facilitating reflection. The action types prompted subjects to reevaluate elements of the activity system and helped describe three potential future activity systems that integrated GPR as a new tool. These findings demonstrate that a participatory take on formative interventions provides a potent means to unveil possible activity systems incorporating emerging technologies. We contribute five formal intervention action types to the literature that equip interventionist researchers with methodological tools to use CHAT in a practice-based study of emerging technologies on construction sites.

Keywords

Activity theory, emerging technology, formative interventions, ground penetrating radar.

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4.1. Introduction

Introducing technological innovations in construction aims to enhance efficiency, productivity, and profitability (Terzis, 2022). This process often leads to changes within the organizational context and the technology itself (Shibeika & Harty, 2015). To better understand how technology and context evolve together, the construction management literature advocates for context-rich, practice-based studies of innovation (Çıdık et al., 2017; Lundberg et al., 2019; Shibeika & Harty, 2015). Commonly, these studies focus on stages of implementation. Implementation studies offer valuable insights into the impact and value of technology already widely used by people in an organization.

One perspective that has supported scholars in developing a holistic and contextual understanding of technology implementation processes is the Cultural Historical Activity Theory (CHAT). CHAT is a theoretical framework that supports exploring how the interplay of social, cultural, and historical factors shapes human activities (Engeström, 2015). It helps examine complex interactions between individuals, tools, rules, and their broader context to understand how activities are situated within specific socio-cultural contexts. Within CHAT, *contradictions* play a central role (Engeström & Sannino, 2011). Contradictions are historically aggravated systemic tensions or conflicts within or between different elements within an activity system. They serve as stimuli for transformative processes and provide a focal point to study change in activities.

In the study of innovation in construction, recent applications of CHAT have used the concept of contradictions to clarify and map the transformation of activity systems – often visually represented through Engeström's triangular activity system framework (2015). Such studies analyze the implementation of *widespread* technological innovations like Building Information Modelling (BIM) (e.g., Mäki and Kerosuo 2015, Nørkjaer Gade *et al.* 2019, Akintola *et al.* 2020, Zomer *et al.* 2020). They rely on observational research, document analysis, and interviews for data collection on contradictions. So far, the researchers in these studies have not 'actively' intervened in the studied activity systems to explore possible future transformations. The nature and advancement of widespread technologies allowed them to follow technology and activities less intrusively, observing and comprehending the natural transformation of technology and activities within their respective contexts.

While previous approaches work for technologies that are adopted and implemented more widely in construction, such as BIM, exploring the possible future impacts of *emerging* technology on activity systems in construction requires a different approach. For one, emerging technologies present a different adoption context as they have yet to become embedded in current organizational practices. Unlike widespread technologies, emerging technologies – such as the ground penetrating radar (GPR), as we elaborate below – represent novel innovations with uncertain future impacts (Pink, 2022; Rotolo et al., 2015). Organizations may not have considered or often hesitate to adopt them due to their inherent uncertainties. This, in turn, limits the possibility for researchers to observe their impacts on construction activity systems. In the case of emerging technology, interviewing and observatory approaches may yield limited or unreliable insights, given that informants lack knowledge and firsthand experience with the innovative technology. Consequently, collecting detailed empirical insights that help reveal contradictions and map the transformations in activity systems becomes particularly challenging.

To address this challenge, researchers can employ one of the methods CHAT literature offers: formative interventions (Sannino, 2011; Sannino et al., 2016). Using formative interventions, the researcher's "role is to intervene by provoking and supporting the [transformation] process led and owned by the learner" (Sannino et al., 2016). In other words, formative interventions involve the deliberate activity researchers conduct to drive practitioners to transform their activity system. The potential benefit of driving such transformations is that they can make the future impacts and value of emerging technology on construction sites more explicit. This insight, in turn, could facilitate more mindful innovation-adoption processes within the construction sector (Swanson & Ramiller, 2004).

Despite this potential, existing formative intervention methods are not adequately tailored to the study of emerging technologies in construction. Formative interventions propose that researchers operate 'outside' the concrete practice as facilitators of change, ensuring that the practitioners lead and own the transformation process (Sannino et al., 2016). This assumed role of the researcher restricts the researcher's capacity for immersive engagement 'inside' the practice. However, an immersive engagement of the researcher-interventionist is necessary when aiming to understand the transformative potential of emerging technology in construction. The lack of knowledge and firsthand experience among organizations and practitioners with the innovative technology means they require external support during practice transformation. While researcher-interventionists could offer such support from within the practice as integral participants, it requires them to navigate the assumed 'boundary' between an outsider's facilitating role and an insider's participating role. Essentially, this necessitates an amended perspective on the researcher-interventionist's proposed and traditionally assumed role during formative interventions. Consequently, the specific actions available to researcher-interventionists from an immersive and participatory role remain unclear.

This study explores how a researcher-interventionist, operating from this amended perspective, can employ the method of formative interventions to gain insights into possible future impacts of emerging technologies on construction activity systems. To achieve this, we analyzed data from an interventionist study where we actively introduced and participated in the use of GPR. GPR is an emerging technology capable of non-intrusive detection of buried utilities that potentially supports the current ‘utility detection activity system.’ In this study, we analyzed how we conducted interventions on twelve construction sites in the Netherlands to explore our role as interventionists in activity system transformations. First, we revisited the field data and employed an inductive coding approach to identify contradictions that triggered activity system transformations. Second, based on these transformations, we delved back into the data to extract descriptions of our interventionist actions that contributed to them. We subsequently classified our actions into five formal intervention action types.

The five action types we found researcher-interventionists can employ in studies of emerging technologies include: [1] shape conditions for emerging technology to be considered by subjects as a meaningful tool solution in the activity system; [2] expose tensions deliberately within the activity system to support subjects in identifying manifestations of contradictions; [3] assist subjects with emerging technology to support them in resolving contradictions; [4] operate as tool operator in the activity system to support subjects in exploring emerging technology; and [5] facilitate subjects’ reflection on existing activity system elements. These action types led to manifestations of contradictions that made practitioners reevaluate their tools, objects, and roles. It allowed the researcher to describe three potential activity system transformations that integrated GPR as a new tool.

In the following sections, we introduce CHAT and the theoretical framework, provide an overview of the utility construction activity under study, and explain our research approach. Before we explain the action types, we describe the identified contradictions and the utility detection activity system transformations. We conclude by discussing how the findings support utilizing our amended formative intervention method in emerging technology studies for construction management research.

4.2. Theory and background

The following three sections sequentially describe the rationale for conducting emerging technology studies in construction, the interventionist approach in our research from an activity theoretical perspective, and the utility detection activity system as our case.

4.2.1. Studying emerging technologies in construction

A spectrum of emerging technologies holds promise to enhance efficiency, productivity, and profitability in construction practices (Ozorhon et al., 2016; Terzis, 2022). Examples include maintenance robots (Koh et al., 2023), virtual reality applications for safety and education (Bao et al., 2022), 3D concrete printers (Chung et al., 2021), and as-built laser scanning techniques (Chen et al., 2022). These emerging technologies are in the initial stages of the product life cycle, meaning they have yet to be standardized in construction practices. This surrounds these and other emerging technologies with uncertainty regarding their future impacts and value (Pink, 2022; Rotolo et al., 2015). Such uncertainty often results in construction organizations hesitating to adopt them. Therefore, studying their potential is difficult for construction management researchers because these technologies still need to be embedded into current organizational practices.

However, construction organizations can make better-informed decisions about technology adoption by developing an early understanding of the potential impact of emerging technology. This, in turn, enhances their ability to adapt better to a rapidly evolving technological landscape. Considering the construction industry's assumed conservative stance on innovation and innovative technology (Winch, 1998), which appears to be increasingly lagging behind other sectors (McKinsey Global Institute, 2017), a context-rich, practice-based perspective on emerging technology and its possible future impact thus has the potential to expedite technology's adoption in construction. CHAT literature introduces an interventionist approach that may benefit such studies, as explained in the next section

4.2.2. Interventions from an activity-theoretical perspective

Cultural Historical Activity Theory (CHAT) originates from the Soviet school of psychology, primarily rooted in the ideas of Vygotsky (1978) and Leont'ev (1978). Their ideas helped to understand how cultural-historical tools or means mediate human action and interaction in the context of other individuals and activities. Engeström expanded upon the theoretical foundation of Vygotsky and Leont'ev by introducing the concept of an 'activity system' (Engeström, 2015). This activity system represents complex, goal-oriented, socially mediated processes where individuals or groups interact with tools, objects, and others in specific socio-cultural contexts. These dynamic systems can be analyzed to understand how people engage in various activities and the factors influencing them. Engeström's expansion toward this model of activity systems has contributed significantly to what is now known as CHAT.

In particular, Engeström (2015) developed his ideas into a conceptual activity system framework for studying the evolution and development of collective work activities. Figure 10 illustrates this activity system framework and its elements. The framework facilitates the visualization of activities, demonstrating how individuals collaborate in socio-cultural and complex environments with dynamically interacting elements. Engeström's framework captures these elements as the actions of subjects (the actors involved in the activity) using tools (both tangible and intangible mediating tools) to transform an object (the central focal point of the activity) into a desired and shared outcome (the realization of the object). The actor's actions part of such transformations are driven by personal sense-making (i.e., sense) and a broader socio-cultural significance (i.e., meaning). Altogether, actors form a community to represent the activity. They take roles through a division of labor, establishing a relational and hierarchical structure within the activity. This system operates within a framework of rules, including regulations, norms, and conventions.

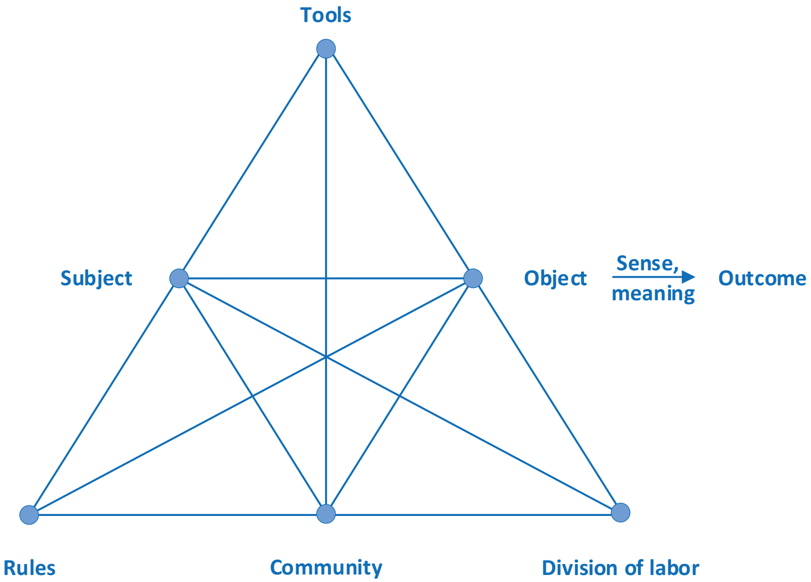

Figure 10. Activity system, recreated from Engeström (2015).

CHAT identifies *contradictions* in or between system elements as the driving force behind transformations of activities (Engeström, 2015). A contradiction can be defined as a fundamental conflict or tension within an activity system. Contradictions are considered historically aggravated and systemic aspects of an activity system. Because they are inherent to the activity system and not something external or easily observable, researchers do not directly have access to contradictions in empirical studies of change. Instead, they approach them through their manifestations, such as observable dilemmas or conflicts (Engeström & Sannino, 2011). These manifestations can help researchers explore change dynamics within activity system transformations.

Researchers can identify four types of contradictions (Engeström, 2015). Primary contradictions take place within an individual element. Such a contradiction arises when a system element faces an internal conflict. In the construction context, this occurs, for example, when a contractor develops a technical solution (i.e., a tool) to solve a construction problem, which may not be the optimal solution since he also cannot exceed a budgetary constraint to still gain revenue from his project. Secondary contradictions take place between elements of an activity. Such a contradiction arises when, for example, conventional two-dimensional design tools used by a contractor may be inadequate to visualize spatially complex three-dimensional structures. Tertiary contradictions occur between the dominant activity systems and an emerging, more advanced form. Such a contradiction arises when, for example, three-dimensional design tools lead to new procedures that do not fit with the existing processes from the dominant activity system that the contractor uses. Quaternary contradictions occur between the dominant activity and an existing neighboring activity system. This contradiction arises when, for example, clients demand a contractor to work with three-dimensional design tools, requiring the very contractor to change his design. This, in turn, may cause resistance within the contractor's activity system.

CHAT provides two fundamental and complementary principles to understand how contradictions drive activity system transformations: *double stimulation* and *ascending from the abstract to the concrete* (Engeström et al., 2014). Sannino (2011) characterizes double stimulation as "the mechanism with which human beings can intentionally break out of a conflicting situation and change their circumstances or solve difficult problems." Within the mechanism of double stimulation, the first stimulus for change is a problematic situation. These problematic situations could arise as manifestations of contradictions. The second stimulus involves using auxiliary tools or artifacts to gain control of and transform the problematic situation. The principle of ascending from the abstract to the concrete emphasizes individuals' learning process to move from an abstract understanding of these problematic situations toward specific, practical, and concrete actions within the activity system to resolve them. Essentially, this learning process, which can be seen as an application of 'expansive learning,' stems from contradictions that must be resolved (Engeström, 2015). Both principles give rise to the phenomenon called *transformative agency*. Transformative agency emphasizes the capacity of individuals or groups within an activity system to actively drive change when undergoing processes of double stimulation and ascending from the abstract to the concrete (Engeström et al., 2014).

The concept of contradictions and the fundamental principles of CHAT have guided two approaches of studies to change. In the first approach, researchers employ the idea of contradictions to gain insight into why and how work activity systems naturally evolve within their context, as seen in studies on the introduction of widespread technologies in construction (e.g., Akintola et al., 2020; Mäki & Kerosuo, 2015; Nørkjaer Gade et al., 2019; Zomer et al., 2020). In this approach, researchers do not 'actively' intervene to trigger contradictions and produce change. Instead, they rely on observations, interviews, and documents for data collection. Conversely, the second approach involves researchers intervening to produce change. They often do so through the method of formative interventions (Sannino, 2011). Researchers use formative interventions to provoke and sustain a transformation process among practitioners (Sannino et al., 2016). By driving these transformation processes, researchers could use formative interventions to make the future impacts and value of emerging technologies on construction sites more explicit.

Various formative intervention methods exist, including the Genetic Modelling Experiment (Zuckerman, 2011), the Clinic of Activity (Clot, 2009), the Fifth Dimension (Cole & The Distributed Literacy Consortium, 2006), and the Change Laboratory (Engeström, 2007; Virkkunen & Newnham, 2013). From these, the Genetic Modelling Experiment models and examines an activity system's change over time. It analyzes how the activity has developed to identify critical stages of change. The Clinic of Activity is used to understand and transform work activities. Researchers engage in dialogues with practitioners to understand their experiences and challenges, aiming to unravel the contradictions and tensions in the work process. The Fifth Dimension method creates a collaborative learning environment where learners are guided by more knowledgeable individuals (e.g., teachers or peers) to reach a higher level of understanding and competence, thereby producing change. Finally, the Change Laboratory involves a structured, collaborative process where participants from different levels and roles within an organization work together to identify and resolve contradictions and challenges in their practices. Through this process, innovative solutions and changes are developed to improve the organization's performance and outcomes.

The four interventionist methods have found applications across diverse fields ranging from healthcare and education to psychology, research, software development, social services, and community development. In these established formative intervention methods, researchers typically assume the role of facilitators of change from a somewhat external standpoint, 'outside' the concrete practice. Their primary responsibility is to create a supportive environment for participants, enabling them to analyze their activities, identify contradictions, and implement changes while ensuring that practitioners lead and own the transformation process (Sannino et al., 2016). This means the researcher never imposes transformations on the practitioners but instead aims to stimulate them to engage in transformation processes that are meaningful to them. For instance, in a Change Laboratory setting, a researcher-interventionist collects empirical material (such as video recordings, observational notes, and conversations with workers) from authentic workplace contexts. This material includes critical incidents, disturbances, and problems, from which the researcher selects and provides extracts for a 'mirror'. This mirror serves to stimulate involvement, analysis, and collaborative efforts among participants during Change Laboratory sessions, fostering the exploration and design of new patterns of activity (Engeström, 2007; Virkkunen & Newnham, 2013).

However, assigning researchers to an 'outside' facilitating role may hinder the effective use of formative interventions in studying emerging technologies in construction. Since these technologies are not yet integrated into current organizational practices, practitioners lack firsthand experience and require external support. Building on the work of Postholm (2020) on using formative interventions in contexts necessitating external support, researcher-interventionists could play a crucial role in providing practitioners with the essential backing to develop knowledge about emerging technology and its application within the practice. Specifically, researchers can offer practitioners firsthand experiences of the technology by participating, potentially fostering their exploration of new perspectives and facilitating the emergence of contradictions that drive transformations.

While this participating role may challenge the prevailing assumption that practitioners should lead and own the transformation process (Sannino et al., 2016), we hold skepticism toward this assumption. From a cultural-historical perspective, an individual's actions are inherently influenced by external factors (Vygotsky, 1978), whether they originate from the researcher-interventionist as an outsider, insider, or from prior experiences. Instead, we align with Van Oers (2013) in emphasizing that practitioners' autonomy during formative interventions should be regarded as their freedom to make sense of their actions and envision new ways of acting. Essentially, practitioners must have the freedom to develop solutions that are meaningful to them and steer transformations according to their views on the purpose of the activity. Hence, we advocate that researchers could act as integral participants within the methodological principles of formative interventions (Engeström et al., 2014), provided they respect this freedom and refrain from imposing transformations.

In other words, we propose that the researcher-interventionist should be allowed to navigate the 'boundary' between their typical facilitating role as outsiders and a new participating role as insiders. Embedding this form of 'boundary crossing' – a concept used by Engeström (1995) to refer to the process by which individuals step outside of their usual roles or domains of activity to engage with unfamiliar territories or practices – in formative intervention studies opens possibilities for active support and intervention by the researcher in addition to the traditional facilitating role. This broadened perspective provides researchers with a more diverse set of tools to provoke and support the practice's transformation process from both the 'outside' and 'inside.'

Since this amended formative intervention approach is underexplored in the literature, this study aims to fill that gap by exploring the necessary actions to fulfill this immersive and participatory interventionist role in studying emerging technology in construction. Before delving into our study of the interventionist role, we provide background information on our research setting, focusing on utility detection.

4.2.3. Emerging technology in the activity system case of utility detection

This section introduces the emerging ground penetrating radar (GPR) technology and the utility detection activity system explored in our study. Detecting buried utilities is a crucial task in construction projects, especially in densely populated urban areas, as it helps reduce the risk of damaging existing infrastructure during excavation (Metje et al., 2007, 2020; Ter Huurne et al., 2020). In the Netherlands, there are *rules* in place that require organizations to accurately verify the location of utilities before digging. To achieve this, construction companies have access to various *tools*. Access to statutory utility records is a standard practice through a centralized platform. Additionally, adhering to a code of conduct, organizations perform trial trenches involving the physical excavation of an area to inspect and record utility locations visually (Lai et al., 2018; Ter Huurne et al., 2020).

However, there are limitations to these methods. Statutory utility records are frequently inaccurate, outdated, or incomplete, and they often lack information about the depth of utilities. Trial trenching is disruptive, expensive, labor-intensive, and provides localized information (Costello et al., 2007; Metje et al., 2007). GPR is emerging as a promising alternative, being a geophysical technology that offers a rapid, cost-effective, and non-destructive way to detect utilities, regardless of their type or material (Lai et al., 2018). The technology works by sending electromagnetic into the subsurface. Changing electric and dielectric properties of the subsurface medium cause the signal to scatter and reflect to the GPR's receiver (Figure 11a). These reflections – for utilities typically visible in hyperbolic shapes – provide the basis for imaging a 'radargram' (Figure 11b). From this radargram, utility depth and, to a lesser extent, size, and material can be inferred.

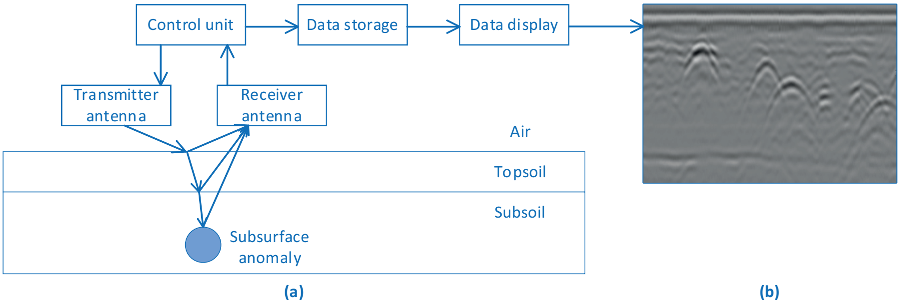

Figure 11. Flowchart ground penetrating radar: (a) process and components of a generic radar system, (b) radargram example displaying hyperbolic shapes (own creation).

While GPR holds promise for utility detection, it faces limited adoption in the construction sector for two primary reasons. First, GPR is a specialized technology with inherent limitations and uncertainties. Factors like soil type, moisture content, and density can disrupt its performance, leading to signal issues (Costello et al., 2007; Daniels, 2008; Jol, 2009; Metje et al., 2008). Additionally, when multiple buried utilities are close to each other, GPR images can become cluttered with overlapping hyperbolic signatures (Costello et al., 2007). These uncertainties have raised doubts about its reliability and suitability for utility detection. Second, in the Dutch context, geophysical methods, including GPR, receive limited promotion in legislation and directives (Ter Huurne et al., 2020). Moreover, the centralized utility maps platform and the legal obligation to precisely determine utility locations before excavation contribute to a hesitancy to incorporate geophysical methods (ibid). As a result, many construction organizations have hesitated to depart from their common surveying methods. Consequently, most organizations lack the experience and expertise to utilize GPR technology effectively.

Essentially, GPR serves as a typical example of an emerging technology. It stands out as significantly novel compared to the common utility detection tools. While it is poised to enter construction sites, its adoption faces challenges. The case of GPR in utility detection activity systems offers a suitable opportunity to study the researcher's role as an interventionist in emerging technology studies.

4.3. Research methodology

This study employed a participatory, interventionist research approach to identify actions that fulfill the interventionist's role in determining the future impacts and value of emerging GPR technology in utility detection activity systems. This involved the first author intervening in twelve utility detection projects in the Netherlands, each with unique site characteristics regarding utilities, ground conditions, and land use. The participants in the activities studied had experience using common utility detection tools but were new to GPR and represented different construction project organizations. The research followed a structured process for our interventions consisting of three phases. These collectively helped identify the action types the researcher-interventionist employed in the GPR case.

In the first phase, we conducted exploratory interviews with key actors from the utility detection projects, including supervisors, project managers, and project clients. These interviews, approximately one hour in duration, served the dual purpose of gaining initial insights into the existing activity system and its socio-cultural aspects while also seeking permission for the first author to intervene with GPR on the construction site. Based on a semi-structured protocol, our questions were aligned with Engeström's activity system framework (2015). We inquired about the common utility detection procedures, the tools in use, reasons behind the hesitance to adopt GPR, objectives in utility detection, expected outcomes, the typical work environment, and any potential constraints imposed by rules like contractual agreements or organizational procedures that might hinder the introduction of GPR. We analyzed the interview transcripts in an open coding round by extracting those quotes that captured instances of activity system elements. In the following coding iteration, we organized these elements within the context of the activity system, considering the elements of the division of labor, subjects, objects, and tools and their interactions primarily.

In the second phase, we obtained onsite access for one to two days to intervene in utility detection activity systems. Having secured permission from supervisors, project managers, or project owners, the first author brought the GPR to twelve construction sites. While the practitioners onsite started their day using their common tools of utility maps and trial trench digging, the researcher simultaneously conducted GPR surveys close to the practitioners (including radar data collection and processing) to identify utility locations. Although this parallel process initially did not spatially interfere with the practitioners' actions, it allowed the researcher to engage in ongoing interactions and spontaneous conversations with the practitioners about the activity and emerging GPR technology, fostering a closer connection between them. Throughout this process, the researcher collected empirical material (i.e., observational notes, pictures, occasional videos, and conversations with workers) about the utility detection activity. This enabled him to explain problem situations to the practitioners, identify manifestations of contradictions in the activity system, and provoke transformation of the activity system.

After the site visits, we revisited the field data and employed an inductive coding approach to identify contradictions that triggered activity system transformations. We first extracted the activity system elements from our field notes using a round of open coding and matched these in the following coding iteration with the elements of the activity system. We then categorized manifestations of contradictions using Engeström's taxonomy (2015) as primary, secondary, tertiary, or quaternary and attributed them to their corresponding activity system elements. Using CHAT's fundamental principles of double stimulation and ascending from the abstract to the concrete, we conceptualized how these manifestations had led to processes of first (learning about and recognizing a problem situation) and second (using an auxiliary artifact to solve it) stimulation among practitioners.

As a third step, we shared our conceptualizations of the identified contradictions in the activity systems by conducting discussions with the same subjects as those interviewed in the first phase. These discussions, lasting approximately 90 minutes, resembled the 'mirror' concept in Change Laboratory sessions. We presented empirical material on problem situations, explained whether GPR had contributed to resolving them, and clarified how those situations had impacted the further continuation of the utility detection project. These discussions stimulated participants' analysis of their activity, enabling them to recognize contradictions and envision future utility detection activity systems, including the potential role of GPR within them. To structure these future visions of the transformed activity system, we used Engeström's activity system framework (2015). This process led to the identification of three potential future activity systems incorporating GPR technology in utility detection activities.

Following these discussions, we revisited the discussion and field data to extract descriptions of our interventionist actions that contributed to the identified transformations in the activity system. We employed an inductive coding approach and extracted our actions from the field notes and discussion transcripts during a first open coding iteration. This process involved identifying instances where our actions had triggered processes of double stimulation and ascending from the abstract to the concrete. By doing so, we linked our actions to the previously identified contradictions that drove the transformations. Subsequently, we organized and classified all actions into formal formative intervention action types during an axial coding iteration. This second coding iteration revealed that in our interventionist role, we fulfilled five action types to produce change. The following section outlines this analysis through the empirical findings from two utility detection projects.

4.4. Findings

The interventions, focusing on introducing and supporting emerging GPR technology in twelve utility detection projects, unveiled formal intervention action types conducted by the researcher-interventionist. This section describes how our interventions triggered contradictions and drove the transformation of utility detection activity systems, employing two cases as illustrative examples. These cases were chosen for their coverage of the three potential integrations of GPR that we identified and their clear examples of the action types associated with the interventionist's role. Additionally, we utilize the empirical insights from these two cases to analyze the interventionist role and actions in facilitating the transformations within the activity systems. We present five formal action types for the interventionist role in emerging technology studies.

4.4.1. Case I: GPR as a complementing, supporting, and substituting tool

Case I illustrates the researcher's role as an interventionist in a utility detection project on an inner-city sewage rehabilitation project. The project's objectives were to (1) *identify connection points* for the new sewer to the existing sewer pumping station to specify engineering parameters and (2) *verify* the utility maps to facilitate mindful excavation during construction. The project manager designated eight locations on the construction site map to dig trial trenches to achieve these. Some of these locations were situated along the sewer line to identify potential connection points, while others were chosen to assess the accuracy of the utility maps. The earlier pre-site visit interview revealed that trial trenches were a standard and common tool for the organization. Neither the project manager nor the organization had prior experience using GPR.

This case demonstrates the transformation of the utility detection activity system toward a collective of activity systems. Together, these transform a set of newly specified objects into the shared and desired outcome of mindful excavation during construction. The objects include the existing object (i.e., documented utilities on utility maps) and two new ones (i.e., anomalies, undocumented utilities, and crossing utilities). GPR plays a role in transforming these objects into a desired and shared outcome (i.e., mindful excavating during construction) in a complementing, supporting, and substituting means to the existing tools. This transformation is illustrated in Figure 12. Three contradictions drove this transformation: a primary contradiction within the existing tools, a secondary contradiction between the existing tools and the existing object, and a primary contradiction within the existing object. We break our role as interventionists down by focusing on the actions that manifested these three contradictions.

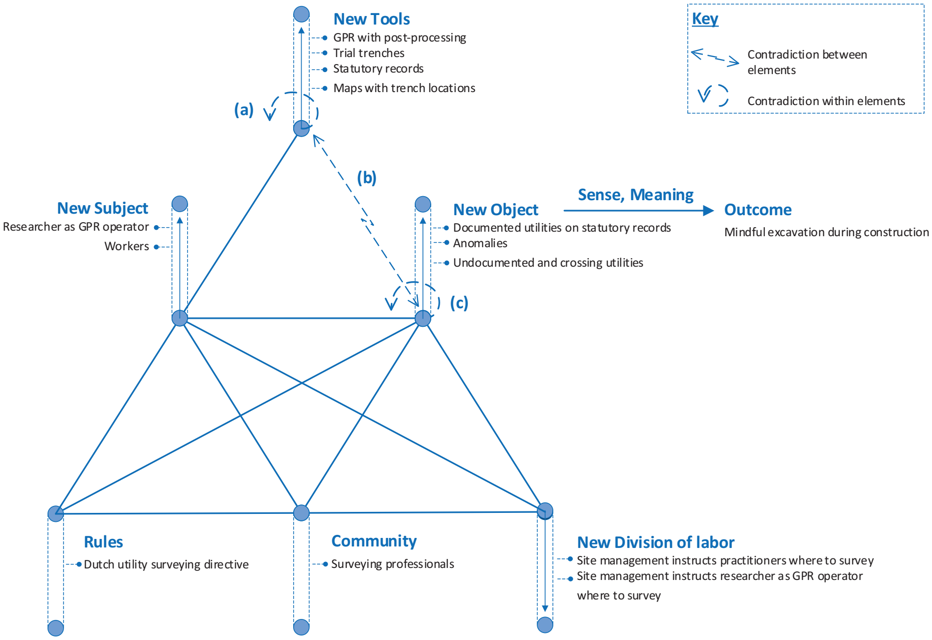

Figure 12. Contradictions and transformations within Case I: (a) transformed tool versus tool (primary contradiction); (b) tool versus object (secondary contradiction); (c) transformed object versus object (primary contradiction.

The researcher's actions started with his arrival at the construction site with GPR. Upon this arrival, the project manager introduced the practitioners to the researcher and informed them that they could discuss with the researcher and ask for the use of GPR to achieve the project's objectives during the day. Being aware of the practitioners' unfamiliarity with the GPR, the researcher subsequently conducted an impromptu GPR demonstration to familiarize and educate the practitioners with the GPR's technical features. Sharing the findings of this demonstration with the project team, the manager responded with interest in GPR's potential use for mapping underground utility lines, albeit with uncertainties: *"[GPR may be] Applicable, yet with uncertainties. I believe many [of the underground utility lines] can be mapped, but our detailed engineering requires an extremely reliable map as input. I guess trial trench excavations remain necessary to achieve this output. For the verification of cables and pipes [and their locations] in general, I have high expectations for GPR, though."* This response indicated that the manager started recognizing the sense of utilizing GPR for the project. Subsequently, the practitioners commenced utility detection tasks while the researcher stayed close, conducting GPR surveys and observing for manifestations of contradictions.

The activities continued until the researcher exposed tensions between the existing tools and GPR as a more time and cost-efficient alternative. The researcher did so by engaging the manager in GPR findings from a survey conducted near a trench dug to verify sewer lines. The radargrams showed that GPR had been similarly successful compared to trial trenches in identifying two sewer lines, as illustrated on the right side of Figure 13. Consequently, the manager emphasized GPR's effectiveness, seeing it as a meaningful alternative to trial trenches for rapidly mapping utility locations without road closure constraints as had been necessary for the trial trench. The researcher's engagement enabled a direct GPR and trial trenching comparison within the activity system, exposing the limitations of existing tools and demonstrating GPR's superior time and cost efficiency. In this case, the manager's realization manifested as a primary contradiction within the existing tools and served as a first stimulus for change.

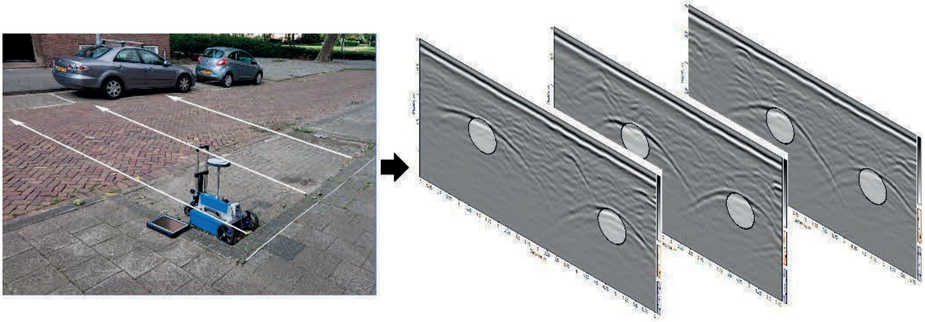

Figure 13. Successful detection of two sewer pipes under a street using ground penetrating radar.

We found that this first stimulus prompted the manager to discuss the value GPR could provide as an alternative tool. To ensure that the project would not encounter delays caused by utility damage or construction issues, the project manager stressed the importance of obtaining more accurate and reliable information about the location of the two sewer pipes. He emphasized this by citing that the inaccurate location of utilities had led to costly return visits in previous projects: "*I want to know where the cables and pipes are as best as possible. We have come back up* *to three times on previous projects as they (i.e., utilities) were not accurately or fully mapped. That should be avoided [for this project]."* Essentially, the emergence of the primary contradiction prompted the manager to question the effectiveness of the existing tools in achieving the utility verification objective. This situation presented a dilemma between, on the one hand, the financial concern related to the possibility of expensive return visits due to inadequate surveying and, on the other hand, the necessity of using trial trenches with no other tools at their disposal. This dilemma manifested as a secondary contradiction between the existing tools and the activity's object, serving as another first stimulus to change.

In response to both first stimuli, the researcher proposed to the manager that he could conduct additional GPR surveys reaching beyond the original eight trial trench locations. Essentially, the researcher suggested actively participating in the activity as the GPR operator. The manager approved, and the researcher proceeded with these additional surveys to verify the positions of the two sewer pipes. Witnessing the successful performance of GPR firsthand prompted the manager to reflect on his previous experiences with common detection tools. He noted: *"Sometimes you find things (i.e. anomalies) during construction that were not on the utility maps. The project must stop, and additional trial trenches are necessary to discover what they are."* He believed that GPR could help prevent such issues, stating: "*We do not plan to locate all cables and pipes within the project. However, it may be important for the preparation of the construction works to locate them. So, while you are here, can you use the GPR to find these quickly?"* Experiencing the GPR firsthand led the manager to recognize the sense of using it to detect anomalies and prepare more effectively for careful excavation during construction.

This learning process emphasized the manager's deepened understanding of the secondary contradiction between tools and objects. It gave rise to a new objective focused on identifying anomalies and locating undocumented and crossing utilities. The manager's realization that transforming the existing object was not always sufficient for realizing an adequate preparation for the organization for later construction phases made him request additional GPR surveys and pre-scanning of trial trench locations. This notion shows the manifestation of primary contradiction within the existing object and a first stimulus for change. The request to use GPR as a solution serves as a second stimulus.

Following the manager's request, the researcher continued his role as a GPR operator and conducted surveys at five additional locations. The researcher engaged the manager in interpreting the radargrams, which led the manager to reflect on the new GPR tool. He stated: "*Although you can say very well that there is something (i.e., underground utilities), it shows it is not always possible to pinpoint each cable or pipe on an individual level. Verifying radar [outcomes] with trial trenches remains important*." This quote emphasizes the manager learning about the limitations in GPR's utility detection capabilities, particularly regarding the project's objective of utility verification. Making sense of this, the manager realized that using trial trenches complementary to GPR was likely necessary.

A week after the site visit, a discussion with the project team helped them envision a future utility detection activity system. The researcher presented his GPR findings, clarifying how GPR had impacted the project. This led to a discussion with the project manager about the technology's value and role in shaping the future of the activity system. The researcher asked the manager to envision the GPR's role as part of this discussion, to which the manager responded that he saw GPR as a tool that could complement, support, or even replace common methods within a collective system of activities. He explained: *"You can effectively demonstrate whether something is present (i.e., with GPR) and use that to dig more targeted test trenches where you encounter something unusual. Based on the radar data, one can decide the interesting locations for test trenches."* He added: *"GPR certainly also offers value on projects where longer utility routes are dug. The radar helps to map such routes more quickly [compared to trial trenches]."* These outcomes of Case I demonstrate that the researcher's actions helped participants develop a meaningful understanding of the potential benefits of GPR for their activity system.

4.4.2. Case II: GPR as a substituting tool

Case II illustrates the researcher's role as an interventionist in a utility detection project on an electricity cables installation project in the inner city. The project's objectives were to (1) *verify* the utility maps to engineer the routing of nine new electricity cables and (2) *locate the water pipeline* as the new cables needed to be installed at a safe distance. Eight specific locations on the construction site map were selected for digging trial trenches to achieve these. Some locations were near the waterline, while others were along potential routes for the new electricity cables. The earlier pre-site visit interview with the project manager revealed that trial trenches were a standard and common tool, and their locations were strategically chosen to balance the need for accurate utility information with a budgetary-constrained approach in mind: "*The goal is to complete the trace as quickly and cost-effectively as possible."* Neither the project manager nor the organization had prior experience with GPR and were largely unaware of its potential for their activities.

This case demonstrates the transformation of the activity system into a substituting activity system that incorporates GPR to transform a new object of subsoil-free space into a set of engineering parameters, as illustrated in Figure 14. Two contradictions drove this transformation: a secondary contradiction between the existing tools used and the existing object and a primary contradiction within the existing object. We break our role as interventionists down by focusing on the actions that manifested these two contradictions.

Like Case I, the researcher's actions started with his arrival at the construction site with the GPR. Following this, the practitioners were informed they had permission to use the GPR that day. The researcher then conducted a GPR demonstration to address the project team's unfamiliarity with the technology. This demonstration piqued the foreman's interest in exploring GPR for verification purposes. He explained: *"I do not really know radar, but I expect it to help predict the location and size of utilities. So while I definitely see an added value, this stands or falls on the reliability and price [of GPR] compared to test trenches."* As in Case I, this response indicated the manager's recognition of the sense of utilizing GPR for the project. Subsequently, the practitioners initiated their utility detection tasks while the researcher remained close, conducting GPR surveys and observing for any manifestations of contradictions.

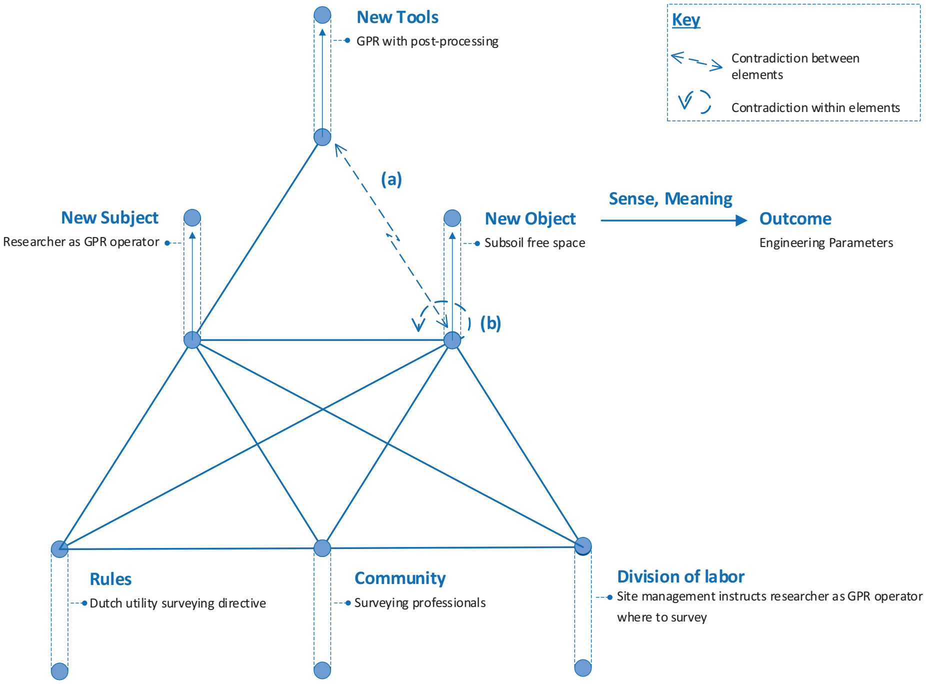

Figure 14. Contradictions and transformations within Case II: (a) tool versus object (secondary contradiction); (b) transformed object versus object (primary contradiction).

Following a similar pattern to Case I, the activities continued until the researcher exposed tensions between the existing tools and GPR as a more rapid alternative for assessing available space for the nine electricity cables. The researcher achieved this by engaging the foreman in the findings from GPR measurements conducted near an excavated trench. The GPR radargram data revealed densely packed utilities, depicted by hyperbolic shapes, as shown on the right side of Figure 15. While this discovery raised concerns about the effectiveness of GPR for verifying utility locations, it also highlighted challenges related to accommodating nine electricity cables due to limited space. The researcher explained to the foreman that despite the pattern similarity across the radargrams, the hyperbolic shapes were so closely packed that they were challenging to differentiate.

The foreman acknowledged this outcome but identified an alternative use for GPR within the activity. He said: *"I can already see from these [GPR] outcomes that it (i.e., the subsoil space) is full. Digging the other trial trenches seems unnecessary because we also already see [based on GPR outcomes that] the cable route will not fit."* The researcher's actions led the foreman to recognize that GPR had successfully identified insufficient free space for the electricity cables. Recognizing the sense of utilizing GPR prompted the foreman to question whether to employ the more accurate yet costly, potentially redundant, and time-consuming trial trenches or use GPR alone to identify free space. This revealed a secondary contradiction between the existing tools and the object. This dilemma served as the first stimulus for change in this case.

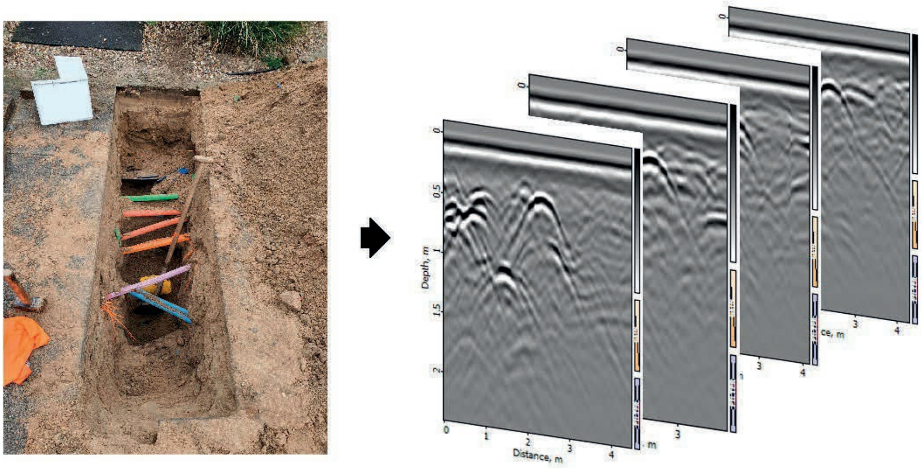

Figure 15. Trial trenches and ground penetrating radar demonstrating a 'full' underground, leaving no free space for nine electricity cables.

Recognizing that the first stimulus could lead to considering GPR as a second stimulus, the researcher proposed to the foreman that GPR could likely assess the availability of subsoil-free space in the other trial trench areas, given their similar utility patterns. This proposal led the foreman to request the researcher to use GPR in addition to digging trial trenches at the remaining locations. Subsequently, the researcher took on an active role as a GPR operator in the activity. In this capacity, the researcher conducted GPR scans at five sites and presented his findings to the foreman and the project manager, who had also arrived onsite. The results demonstrated that GPR was as effective as trial trenches in revealing insufficient free space at these locations.

The firsthand exploration of GPR alongside existing tools enabled the foreman and project manager to compare the two directly. This experience prompted them to discuss the project's tool usage with the researcher. The manager commented: *"The radar would have been a proper substitution on all locations where we have dug trial trenches. Your scans quickly make it clear that the underground is full. Especially where digging trial trenches is extra difficult, the radar would have been worth it. This particularly mattered for the very costly trenches where we had to dig in polluted soil."* In agreement with the foreman, the manager's statement indicated that he also considered GPR an equally effective alternative to trial trench tools for this project. He confirmed that GPR was more cost- and time-efficient, especially in areas with polluted soil. This realization emphasizes a learning process that deepened the practitioners' understanding of the dilemma they faced when choosing between these tools, previously identified as the primary contradiction in their existing tool usage. It demonstrates that by experiencing GPR firsthand, the practitioners recognized the sense of using it as an alternative to trial trenches.

Similar to Case I, a post-site visit discussion with the project team assisted them in envisioning a future utility detection activity system. The researcher shared his GPR findings, clarified how GPR had impacted the project, discussed with the project team how they perceived the technology's value and role, and asked them to envision this future role in the utility detection activity. In response, the manager stated: *"There are limitations to using the GPR technology, but there are many situations where highly accurate information about the utilities is unnecessary. The findings onsite show that GPR works well in appointing the free space."* In the current activity system, trial trenches were used to verify utility maps and locate the water pipeline, a level of detail that GPR could not provide. However, exploring GPR firsthand helped the manager recognize its value in determining free space availability. The manager's realization that transforming the existing object of the activity was not essential for the desired outcome signaled the manifestation of a primary contradiction within the object. This prompted him to envision a future activity system with a transformed object and GPR as an integral tool. The outcomes of Case II hence demonstrate that the researcher's actions facilitated the participants' development of a meaningful understanding of the purpose of their activity and the potential benefits of GPR in supporting it.

4.4.3. Five action types for researcher-interventionists in emerging technology studies

The findings from Cases I and II outline the potential transformations of the utility detection activity systems toward three future activity systems incorporating GPR as a new tool: a complementary system integrating GPR as a tool for transforming the original detection object, a supporting system using GPR before pursuing transformation of the original detection object, and a substituting system using GPR for transforming a new detection object. We identified five formal action types the researcher-interventionist can employ to identify such future impacts: [1] shape conditions for emerging technology to be considered by subjects as a meaningful tool solution in the activity system; [2] expose tensions deliberately within the activity system to support subjects in identifying manifestations of contradictions; [3] assist subjects with emerging technology to support them in resolving contradictions; [4] operate as tool operator in the activity system to support subjects in exploring emerging technology; and [5] facilitate subjects' reflection on existing activity system elements. Table 3 presents these types and provides examples from the two cases to illustrate how they were operationalized in the study.

The first action type focuses on *shaping conditions for subjects to consider emerging technology as a meaningful tool solution when contradictions manifest*. Through active engagement and education about innovative technology, researchers can instill an understanding of its value among subjects. This newfound knowledge leads them to view GPR as a meaningful and practical problem-solving tool when facing problematic situations. Both cases follow a similar sequence of actions for this first type: subjects are informed that they can include GPR as an option in their toolbox, followed by an impromptu demonstration by the researcher where findings are shared with the project teams. In Case I, this sequence prompted the manager to express interest in further exploring GPR's utility detection abilities that day for verification purposes. Case II mirrored this outcome, with the foreman expressing interest in GPR. Essentially, the first action type creates an environment conducive for subjects to consider emerging technology in their actions as a second stimulus for resolving contradictions.

To enable emerging technology to serve as a second stimulus, researchers can *expose tensions deliberately to support subjects in identifying and learning about contradictions within the activity system*. This second action type guides subjects in recognizing and learning about the systemic contradictions in their activity system. For example, in Case I, the researcher supported subjects in unveiling primary contradictions in the use of existing tools by showcasing GPR's success compared to trial trenches. This prompted the project manager to compare GPR with the common use of trial trenches, revealing to him the limitations of existing tools while learning that GPR surpassed these tools in both time and cost efficiency. Hence, researchers can deliberately trigger a first stimulus for change through this second action type.

When subjects identify contradictions independently or through tensions the researcher exposes, researchers can *assist subjects with emerging technology to resolve them*. This third action type opens up possibilities for the active support of the researcher, creating a setting where practitioners can experience the innovative technology firsthand. For example, in Case I, the researcher responded to the project manager's request by using GPR at five additional surveying locations to resolve a primary contradiction within the existing object. In Case II, the researcher proposed using GPR to resolve a secondary contradiction between the existing tools and the object.

Table 3. Five action types for researcher-interventionists in emerging technology studies, exemplified through the case of GPR.

Action type	Example actions from the GPR case
Shape conditions for subjects to consider emerging technology as a meaningful tool solution when contradictions manifest.	Ask permission to intervene with GPR on the construction site.
	Educate practitioners about the features and components of emerging GPR technology.
	Engage practitioners in the survey outcomes of the emerging GPR technology.
Expose tensions deliberately to support subjects in identifying and learning about contradictions within the activity system.	Inform practitioners about anomalies between the utility locations on the utility maps and findings from the emerging GPR technology.
	Enable practitioners to compare the outcomes of existing tools with those from the emerging GPR tool.
Assist practitioners with emerging technology to support them in resolving contradictions.	Conduct additional GPR surveys in response to a request to resolve a primary contradiction within the existing objectives.
	Propose emerging GPR technology as an alternative means of utility surveying to resolve a secondary contradiction between tools and objectives.
Operate as a tool operator in the activity system to support subjects in exploring emerging technology.	Provide practitioners firsthand experiences of the emerging GPR technology by operating and moderating its use as an alternative to existing tools.
Facilitate subjects' reflection on existing activity system elements and encourage them to envision future developments.	Share conceptualizations of the identified contradictions with the practitioners.
	Clarify how the emerging GPR technology has impacted the further continuation of activities.
	Ask practitioners to envision the emerging GPR technology's role in future systems.

The third action type introduced a fourth and highly participatory action type: *operating as a tool operator in the activity system to support subjects in exploring emerging technology*. The researcher's firsthand guidance in operating and moderating GPR proved essential for the identified activity system transformations as subjects lacked prior experience with the innovative technology. In the capacity of the GPR operator, the researcher facilitated the integration of the technology into the activity. This fourth action type empowered the subjects to embed GPR in the activity system as a second stimulus for change.

Through this immersive fourth action type, the researcher facilitated practical exploration and learning about the value of emerging technology for the subjects' practice. This immersive learning process encouraged the exploration of new perspectives, ideas, or approaches among practitioners, fostering a context for contradictions to manifest and resolve. For example, in Case II, exploring GPR alongside existing tools allowed subjects to directly compare the value of these tools in transforming the activity's object into the desired outcome. This comparison prompted them to question the specification of the existing object, serving as a first stimulus for change and revealing a primary contradiction in the activity's object. Similarly, witnessing the successful use of GPR in Case I, after being asked to resolve a contradiction between existing tools and the activity's object, led the project manager to recognize a primary contradiction in the object. In other words, the firsthand learning through the fourth action type enabled practitioners to acknowledge the practical sense of using GPR in their activity as a problem-solving tool, akin to a second stimulus for change. This use of GPR in the concrete practice by the researcher hence initiated multiple cycles of double stimulation. Within these cycles, subjects transitioned from abstractly understanding contradictions to engaging in specific, practical, and concrete actions within the activity system to comprehend and address them with GPR technology.

Finally, we discovered that *facilitating subjects' reflection on existing activity system elements and encouraging them to envision the future* enables researchers to capitalize on the firsthand experiences of subjects with emerging technology. This process of reflection helps individuals transition from understanding the theoretical potential impact of a technology, which was initially introduced by the researcher with the first action type, to considering how it affects their day-to-day work environment. By drawing on their practical experiences, introduced by the researcher through action types three and four, researchers can guide subjects in envisioning future activity systems by stimulating practitioners to recognize emerging technology as a meaningful tool for resolving problem situations and by prompting purposeful inquiries about their vision for the activity system's future and the technology's potential role. Essentially, this fifth action empowers subjects with transformative agency to shape and steer the future of their activity system based on their reflections and views. It stimulates practitioners to ask themselves, *"What does the use of the technology mean for me and the activity?"*

This study's reflective processes contributed to conceptualizing three potential futures for using GPR. The subsequent section delves into the implications of our findings and the five action types for construction management literature and CHAT.

4.5. Discussion

This interventionist study revealed potential transformations of utility detection activity systems toward future systems incorporating emerging GPR technology as a tool. We found potential changes to activity system elements (e.g., tools, objects, subjects) due to manifestations of contradictions. While learning about these contradictions, practitioners were prompted to reconsider activity system elements and envision future change. In the role of researcher-interventionist, five action types supported these transformations. This contributes to the literature as follows.

First, we provide evidence that interventionist approaches support the construction management literature by providing a methodology to study future impacts of emerging technologies on construction sites. Our specific focus centers on the method of formative interventions, which involves the deliberate activity by researchers within an activity system to provoke and drive a transformation process among practitioners (Sannino, 2011; Sannino et al., 2016). In contrast to the prevailing observational CHAT applications in construction management literature, often focusing on widespread technologies like BIM (e.g., Akintola et al., 2020; Mäki & Kerosuo, 2015), we show that amending formative interventions with a participatory perspective offers a powerful combination for researchers to trigger transformative processes and reveal future activity systems for emerging technologies. This combination allows them to cross the boundary of the concrete practice and become active participants in the activity system. Our study demonstrates how researchers can use this renewed take on formative interventions to develop theories of change using the methodological principles underpinning the CHAT interventionist approach: *double stimulation* and *moving from the abstract to the concrete* (Engeström et al., 2014).

Essentially, our findings reveal that our amended take on formative interventions enables researchers to initiate processes of double stimulation among practitioners. This involves guiding them through a transition from theoretical understandings of their system's contradictions to practical and concrete insights about actions to resolve these contradictions with emerging technology. Considering the ongoing proliferation of various emerging technologies in the construction industry, including maintenance robots (Koh et al., 2023), virtual reality applications for safety and education (Bao et al., 2022), 3D concrete printers (Chung et al., 2021), and as-built laser scanning techniques (Chen et al., 2022), we advocate that our study and this amended take on the formative interventions method provides valuable methodological insights for construction management research. It supports researchers seeking context-rich, practice-based perspectives on the future impacts of emerging technology in construction activity systems.

Second, we flesh out our interventionist role by introducing five formal intervention action types that researchers can employ when conducting studies on emerging technologies in construction. These five action types include: [1] shaping conditions for emerging technology to be considered by subjects as a meaningful tool solution in the activity system; [2] exposing tensions deliberately within the activity system to support subjects in identifying manifestations of contradictions; [3] assisting subjects with emerging technology to support them in resolving contradictions; [4] operating as tool operator in the activity system to support subjects in exploring emerging technology; and [5] facilitating subjects' reflection on existing activity system elements. This study illustrates how the researcher-interventionist applied these five action types to identify three potential transformations within the activity systems for the GPR case. Each of these transformations represents a distinct 'use case' for this emerging technology.

This 'phronetic' type of knowledge follows from a close understanding of our empirical findings from practice rather than being considered a universal rationality (Petersén & Olsson, 2015). Specifically, we identified uses for GPR in utility detection activities as a *complementary*, *supporting*, or *substituting* tool for the existing tools, exceeding its conventual use of utility verification. Therefore, the five action types introduced in our study offer methodological tools for researchers to uncover such future uses. We advocate that the insights gained from employing our approach could facilitate more mindful innovation-adoption processes (Swanson & Ramiller, 2004). In particular, construction organizations can engage in more informed decision-making when equipped with a meaningful understanding of the innovative technology during adoption decision-making and implementation processes. In the case of GPR, this enhanced understanding may stimulate higher adoption rates (Lai et al., 2018), supporting the increasingly complex construction projects in urban areas (Metje et al., 2020).

Third, our interventionist approach and action types enrich the current CHAT toolbox of formative interventions by proposing a renewed participatory take on the role of the researcher-interventionist. This approach stands apart from established methodologies like Fifth Dimension (Cole & The Distributed Literacy Consortium, 2006), Change Laboratory (Engeström, 2007; Virkkunen & Newnham, 2013), Clinic of Activity (Clot, 2009), and Genetic Modelling Experiment (Zuckerman, 2011) by actively immersing the researcher in practice. By doing so, we challenge the conventional assumption that transformation processes must be led and owned by practitioners (Sannino et al., 2016) and propose that the researcher crosses the 'boundary' of concrete practice – an idea articulated by Engeström et al. (1995) to describe individuals stepping outside their usual roles.

Our findings demonstrate that researchers can directly engage with practitioners' activities through this boundary crossing. Through our five action types, we provide methodological insights on how researchers, as integral participants of an activity system, can foster tensions that lead to contradictions while respecting practitioners’ freedom to interpret their actions and envision new ways of acting (Van Oers, 2013). We argue that ‘participating’ does not necessarily entail participating in how the transformation unfolds. Instead, we demonstrate that researchers enhance their ability to stimulate practitioners’ engagement in learning and transformation processes by actively participating in the actual activities. Therefore, we propose that adopting a participatory role as outlined in this study enhances researchers’ facilitating capabilities while preserving practitioners’ transformative agency (Engeström et al., 2014). We articulate that this broadened role of the researcher is particularly beneficial in contexts requiring external support, aligning with previous applications of formative interventions in the context of education (Postholm, 2020).

This departure from established formative intervention methods proved essential in our study of the emerging GPR technology. Since the practitioners had limited to no experience with the technology, our support provided practitioners with the essential backing to develop knowledge about GPR and its application within the practice. Through our participatory role, we found that providing the practitioners with firsthand experiences of the GPR technology enabled them to develop a meaningful understanding of its potential benefits. The researcher’s active involvement in using GPR within the practice led practitioners to recognize the sense of utilizing this technology, ultimately facilitating its practical application and allowing them to continue exploring its benefits. Had the researcher not participated, the activities under investigation likely would have continued as usual, with subjects potentially failing to recognize or learn about contradictions. This limited learning could have diminished their incentives to change, maintaining the status quo of the activity, as seen in our earlier work (Ter Huurne et al., 2022). Instead, by immersing a researcher-interventionist in the studied activity from a participatory research perspective, our research highlights how we enabled practitioners to understand the contradictions within their activity system and consider emerging technology as a meaningful tool solution to resolve them.

The proposed interventionist approach also brings forward limitations and recommendations for future research. For one, our participatory role comes with responsibilities and challenges. Becoming an integral part of the activity system means researchers must maintain transparency about their role and objectives, reflect on their impact on the system, and consider how they influence the changes that practitioners produce. Failure to do so could result in the ‘Hawthorne effect’ (Oswald et al., 2014). Furthermore, researchers should avoid imposing transformations on practitioners during formative interventions. Instead, they should ensure practitioners’ autonomy by allowing them the freedom to interpret their actions and envision new ways of acting (Van Oers, 2013), in line with CHAT’s principle of transformative agency (Engeström et al., 2014). This means researchers must engage in a manner that supports the transformation process without overshadowing the participants’ agency for change and, thus, their views on how to transform the activity system. This especially asks researchers to be considerate in using the proposed action types [2], [3], and [4] of this study.

Additionally, our study predominantly focused on the activity itself, with a specific emphasis on how we, as researcher-interventionists, could facilitate the transformation of this activity to uncover the future impacts of emerging technology. In doing so, we paid less attention to the learning processes that participants engaged in as we triggered the processes of double stimulation and ascending from the abstract to the concrete through our actions. CHAT offers the model of ‘expansive learning’ by Engeström (2015), which can help uncover the underlying dynamics of learning when practitioners are exposed to formative interventions. This model applies the principle of ascending from the abstract to the concrete and highlights how individuals progress from understanding abstract concepts to implementing them in concrete situations (Engeström, 2020). It could be valuable to employ the cycles of expansive learning to gain a deeper understanding of the impact of our interventionist role on the innovative actions taken by practitioners and their role in driving transformations within the activity system.

The outcomes of our interventions are also limited to locally generated transformations (Sannino et al., 2016). While this approach is valuable for capturing the complexity and dynamics of construction practices, as illustrated in our GPR case, the outcomes of this approach are often challenging to reproduce and generalize across the entire domain. Thus, while our case demonstrates how various empirical landscapes influenced the utility detection activity system transformation process, we also observed that the chain of events creating transformation processes and the final identification of system transformation occurred differently among the cases. Future studies should, therefore, explore how locally identified contextual knowledge can be transformed into domain-appropriate knowledge for emerging technologies. This might be achievable by connecting insights from local activity system studies with frameworks that offer a more systemic perspective, such as Constructive Technology Assessment (CTA), which helps anticipate technology’s impact in terms of its legitimacy, acceptance, and adoption (Schot & Rip, 1997).

Finally, during our study, we identified the need for new skill roles to bring about change. For example, the researcher acted as the GPR operator in our research, as construction practitioners lacked the experience or skills to use the technology. Our presence helped avoid a secondary contradiction between the subject and the tools, which might have emerged if the practitioners had attempted to use the technology themselves in the future without support. Although our primary purpose was not to resolve all contradictions in our study but to explore the interventionist role in uncovering activity system transformations, it is crucial to acknowledge that introducing emerging technologies will likely create contradictions requiring resolution in subsequent adoption stages. Practitioners should carefully consider these contradictions to ensure the successful transformation of the activity and implementation of the emerging technology.

4.6. Conclusions

This study explored how researchers, as interventionists, can employ the method of formative interventions with a broadened participatory positioning of the researcher to gain insights into possible future impacts of emerging technologies on construction activity systems. We focused on the emerging ground penetrating radar (GPR) technology and actively introduced and supported practitioners in its use in utility detection activity systems across twelve construction sites. Our analysis involved scrutinizing the actions required to fulfill the interventionist role through an inductive coding approach, utilizing data collected from interviews, field visits, and discussions. This analytical process included identifying contradictions that triggered transformations in the activity system, matching them with our specific interventionist actions, and categorizing these actions into distinct action types. The process revealed five formal intervention action types, contributing to the literature as follows.

First, we provide evidence that interventionist approaches support the construction management literature by offering a methodology for studying the potential future impacts of emerging technologies on construction sites. In contrast to the prevailing applications of Cultural-Historical Activity Theory (CHAT) in construction management literature that often focus on widely adopted technologies like Building Information Modelling (BIM), we demonstrate that participatory, interventionist approaches offer a potent means to unveil possible activity systems incorporating emerging technologies.

Second, our study introduces five action types that researchers, in their role as interventionists, can employ when exploring potential future impacts of emerging technologies: [1] shape conditions for emerging technology to be considered by subjects as a meaningful tool solution in the activity system; [2] expose tensions deliberately within the activity system to support subjects in identifying manifestations of contradictions; [3] assist subjects with emerging technology to support them in resolving contradictions; [4] operate as tool operator in the activity system to support subjects in exploring emerging technology; and [5] facilitate subjects' reflection on existing activity system elements. These action types led to manifestations of contradictions, prompting practitioners to reevaluate their tools, objects, and roles. It led to identifying three potential activity system transformations that integrated GPR as a new tool.

Third, our interventionist approach and action types broaden the current CHAT toolbox of formative interventions by proposing a participatory role for the researcher-interventionist. This study illustrates how tensions arise and contradictions manifest when the researcher directly engages with practitioners' activities. Our approach challenges the assumption that practitioners must lead and own transformation processes. This perspective can restrict the utility of formative interventions in contexts requiring active support, such as implementing emerging technologies unfamiliar to practitioners. Instead, we demonstrate that a participatory positioning can coexist with the sense and meanings attributed by practitioners to the activity's purpose, enabling the researcher to assist practitioners in developing meaningful solutions to the contradictions that manifest. Our findings show that this approach does not undermine practitioners' transformative agency but rather respects their perspectives on how to transform the activity system.

To deepen our understanding of the interventionist role and action types, we recommend further exploration of the underlying learning processes driving innovative actions by subjects. Engeström's expansive learning model (2015) could be valuable in this regard. Furthermore, we suggest that future research explores systemic perspectives guiding the evolution of locally identified solutions through the lens of CHAT, aiming at domain-appropriate knowledge. This approach could support harnessing the three 'use cases' identified in our GPR study, shaping adoption decisions, and facilitating the future implementation of the emerging technology on a systemic level.

Chapter 5

outlining local GPR deployment strategies into a dataset that details the construction site setting

Ground penetrating radar at work: A realistic perspective on utility surveying in the Netherlands through a comprehensive ground-truth dataset

Abstract

This dataset provides a comprehensive compilation of ground penetrating radar (GPR) surveys across 125 utility surveying activities in the Netherlands. The dataset details the specific use of GPR in each authentic real-life utility surveying activity, whether employed independently or as a complementary tool alongside existing surveying methods, with or without post-processing. The dataset includes 959 radargrams, ground-truth information obtained from trial trenches, and an inventory of construction, geophysical, infrastructural, and technical features. The GPR utilized in all activities is an air-coupled radar with a 500 MHz frequency antenna, a GNSS RTK positioning system, and a measuring wheel encoder. This ground-truth dataset provides researchers with a valuable resource to further assess the practical efficacy of GPR as a utility surveying method, refine radargram processing algorithms and techniques, and explore the possibilities of predictive modeling.

Keywords

Construction, ground penetrating radar, ground-truth, practice, utility surveying.

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5.1. Background

As construction projects increasingly involve works with or adjacent to subsurface utilities, the demand for accurate and comprehensive information regarding their locations and attributes becomes critical. This need stems from the ongoing growth and urbanization of societies, advancements in communication technologies, and the active pursuit of long-term agendas such as energy transition and climate adaptation (European Commission, 2021). Organizations preparing for construction works rely heavily on obtaining this information, as failure to do so can result in utility strikes; a significant issue within the sector, demonstrated by the nearly 47 thousand reported instances in the Netherlands alone in 2022 (RDI, 2023). Existing literature advocates for adopting ground penetrating radar (GPR) as a geophysical detection technology to assist construction organizations in better utility detection (Lai et al., 2018).

GPR is a geophysical method offering a non-intrusive and rapid means of utility surveying (Utsi, 2017). This technology operates by transmitting electromagnetic signals into the subsurface, where variations in the electric and dielectric properties of the medium cause the signal to disperse and reflect back to the GPR receiver. These reflections, typically manifesting as hyperbolic shapes for utilities, serve as the foundation for generating a ‘radargram.’ Through analysis of this radargram, utility depth and, to a lesser extent, dimensions and material composition can be deduced. While the radar is always considered to provide the ‘right’ information, it remains essential to interpret its outcomes and determine how to use them in a practical work context (Utsi, 2017). Therefore, ongoing research focuses significantly on GPR’s utility detection capabilities with an emphasis on optimizing radargram processing (Bai & Sinfield, 2020; Ghanbari et al., 2022) and exploring innovative and experimental (3D) scanning techniques (Šarlah et al., 2020; Siu & Lai, 2019).

However, the majority of existing research on GPR is conducted within controlled laboratory settings, limiting its generalizability to the complexities and uncertainties encountered in real-world applications. Real-world scenarios present challenges such as non-homogeneous subsurface mediums, closely packed utilities installed in non-linear patterns, uncertainty in utility locations, and the context-specific surveying requirements of construction organizations. Consequently, there often exists a disparity between the outcomes of laboratory-based studies and construction organizations' anticipated value of GPR. This disparity has led to the frequent ‘failure’ of GPR applications (Lai et al., 2018; Lai & Sham, 2023), as construction teams’ surveying requirements could not be adequately addressed. Consequently, there is a noticeable lack of consideration for GPR in surveying practices within the construction industry. A realistic assessment of the value of GPR in authentic utility surveying scenarios is, therefore, necessary to expedite its adoption in the construction context.

This article provides an empirically rich dataset derived from applying GPR in real-life utility surveying activities. The value of this dataset lies in its ability to provide researchers with empirical data that encapsulates the intricate complexities of real-life utility surveying scenarios. This data can be used to (1) evaluate the practical capabilities of GPR as a detection technology across an expansive array of utility surveying conditions, (2) assess and refine radargram processing algorithms and techniques, and (3) train and develop predictive machine learning-driven models that anticipate the applicability of GPR in forthcoming surveying activities

5.2. Data description

This article outlines a dataset encompassing 125 utility surveying activities conducted across thirteen construction projects in the Netherlands between April 2020 and March 2021 (Ter Huurne, 2023). These projects were situated in or around various Dutch cities and towns, including Enschede, Eindhoven, Arnhem, Zwolle, Helmond, Helvoirt, Berkel-Enschot, Rotterdam, Zaandam, Oudewater and Feanwalden (Figure 16). The projects in the dataset are identified numerically from one to thirteen. More data may be added to the dataset in the future.

Figure 16. Map of project locations spread across the Netherlands.

The dataset includes filtered metadata for each surveying activity, describing how a ground penetrating radar (GPR) was applied and under what conditions the activity occurred. These condition features are grouped into three categories: construction management-, construction site-, and technical-related features. The construction site-related features are divided into below-surface features (i.e., ground condition, utility infrastructure, and anomalies) and above-surface features (i.e., terrain type and surroundings). Figure 17 provides an overview of the taxonomy of the metadata. The metadata for all surveying activities is captured in a .csv file. A codebook, which details each feature, its attributes, and its values, is also enclosed in the dataset.

The primary focus of the dataset revolves around detailing the application of GPR in utility surveying activities. The dataset differentiates among three types of GPR methods: the standalone method of GPR with post-processing of radargrams (referred to as ‘0’ in the dataset), the standalone method of GPR without post-processing of radargrams (referred to as ‘1’), and the complementary method of GPR alongside trial trench verification (referred to as ‘2’). Both standalone methods denote the use of GPR as an independent surveying technique capable of meeting the specific surveying requirements of the activity. Depending on whether post-processing is necessary in a given case, the dataset distinguishes between these two as components of the standalone application of GPR. In instances where GPR alone could not meet the surveying requirements of the activity, it was employed as a complementary method alongside trial trenching. The choice of method was guided by the expertise of the GPR operator and the proficiency in interpreting radargrams. Throughout all activities, the same GPR operator, who demonstrated a high level of skill in both the operational and interpretative aspects of GPR usage, was involved.

The dataset provides information about the conditions governing the application of the specific GPR method. The construction management-related features outline utility surveying objectives, planned construction works, accuracy requirements, and additional construction activities. Most surveying activities in the dataset were geared toward validating existing utility maps, frequently together with utility replacement or installation works. Construction organizations commonly did not mandate pinpoint accuracy in determining utility locations.

The construction site-related features are described through both below-surface and above-surface features, complemented by the general condition of the weather. Below-surface features provide insight into the ground conditions within the surveying area, the existing utility infrastructure, and the identification of anomalies. Specifically, ground conditions detail the soil’s relative permittivity, the relative groundwater level compared to utility depth, and the soil type. The dataset predominantly focuses on urban areas with sandy ground conditions, with a few instances involving clayey soil types. Notably, most utilities were situated above the groundwater level.

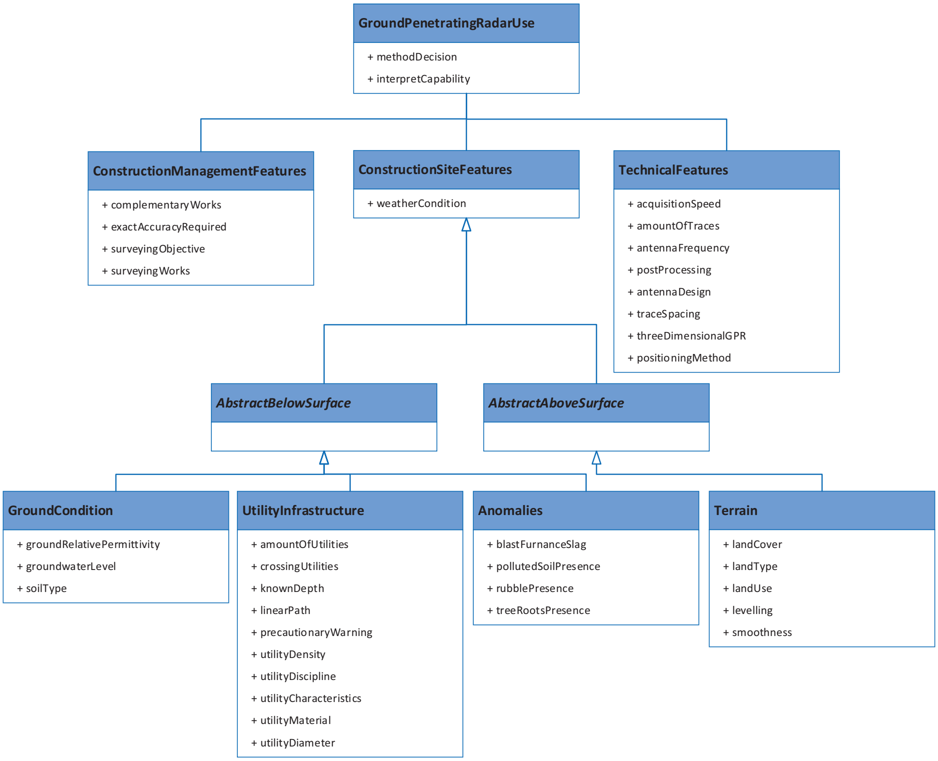


Figure 17. Taxonomy of the dataset.

The infrastructural features describe the utilities as found onsite. This includes the amount of utilities and their respective disciplines, materials, and diameters. Additionally, it notes whether there was an elevated risk of utility strikes, if the depth of the utilities was known, whether utilities were crossing, and the orientation of their paths (linear or curved). In the surveyed areas within the dataset, a minimum of 2 utilities and a maximum of 23 utilities were identified. Utility disciplines encompass water, electricity, oil/gas/chemicals, sewage, and telecommunications, with diameters ranging from 16 mm to 1326 mm. Some activities were flagged with an increased risk of utility strikes. Most utilities followed a linear orientation. The dataset includes notes for specific utility conditions, such as being shielded with a cover, bundled, featuring a diameter or material transition, or installed in a conduit (a larger pipe designed to protect inner utilities).

The dataset also specifies the presence of anomalies in the subsoil. Four types of anomalies were considered, namely the existence of blast furnace slag, polluted soil, rubble, and tree roots. Across the dataset, anomalies were typically found to a limited extent, with rubble being the most frequently observed among the four types.

The above-surface features provide insights into the type of terrain and environment where the surveying activity occurred. Specifically, the terrain feature outlines the land cover, type, and use, along with the leveling and smoothness of the terrain. While most surveying occurred on paved surfaces such as sidewalks, streets, and parking areas, unsurfaced surfaces like greenery were also present.

The technical-related features outline the operational and technical details concerning the application of GPR. Specifically, they describe the acquisition speed of GPR data collection, the number of traces collected and their spacing, the GPR antenna design type and its frequency, the employed positioning method for utility location determination, whether post-processing of radargrams was conducted, and if the GPR facilitated the collection of three-dimensional data. The same GPR equipment was consistently used across all surveying activities, as further elaborated in the design, materials, and methods section.

Alongside the filtered metadata, the dataset includes the surveying data itself. These were gathered through GPR and trial trenching methodologies. The data repository offers raw and georeferenced radargrams and an overview of processed ground-truth data per surveying activity. Radargram counts per activity range from 2 to 26, culminating in 959 radargrams for the entire dataset. Figure 18 presents one of the included radargrams. Additionally, for each activity, survey lines are visualized on a map together with the orientation of the trial trench, as seen in Figure 19.

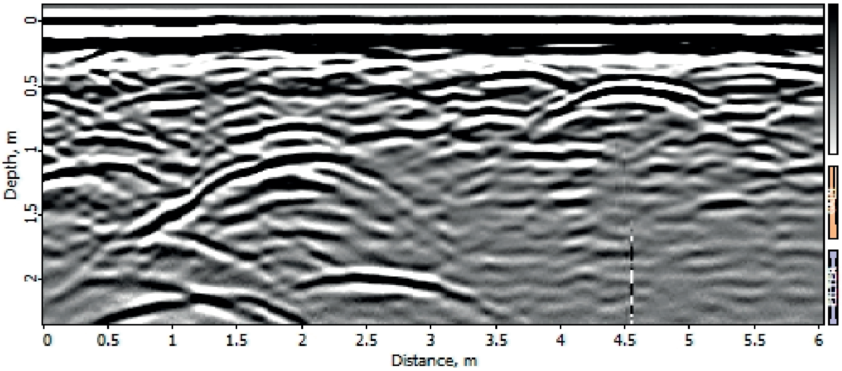


Figure 18. Example output of a radargram (.sgy).

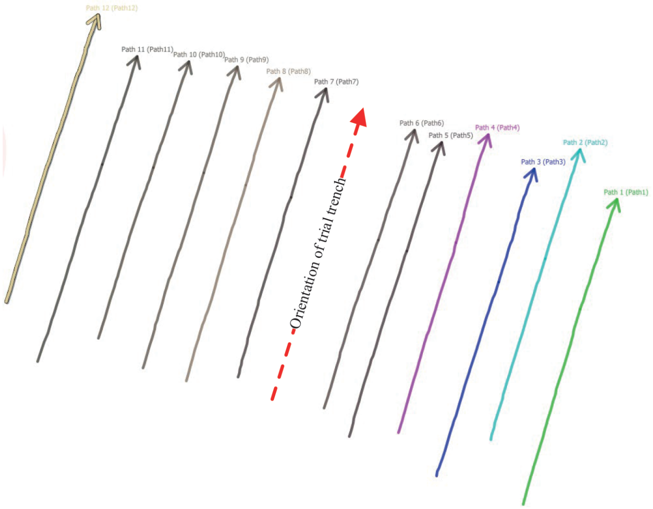
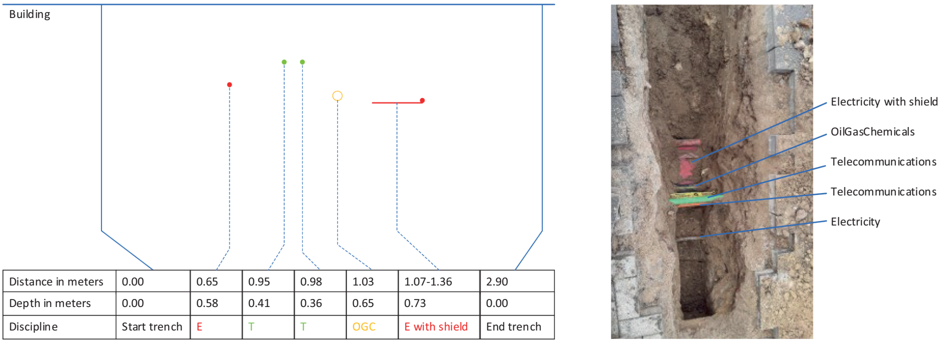


Figure 19. Map of radargrams including orientation of trial trench (.png).

Each activity comes with corresponding ground-truth data collected through trial trenching. The processed ground-truth data provides cross-sections of the trenches detailing utility location and their type, captured images of the exposed utilities, or a combination of these. Figure 20 provides an example of how ground-truth data for one of the activities is depicted within the dataset. Notably, the ground-truth data lacks georeferencing due to confidentiality constraints. Geospatial information has been omitted to preserve data and utility location confidentiality. The radargrams, however, are georeferenced.



Distance in meters	0.00	0.65	0.95	0.98	1.03	1.07-1.36	2.90
Depth in meters	0.00	0.58	0.41	0.36	0.65	0.73	0.00
Discipline	Start trench	E	T	T	OGC	E with shield	End trench

Figure 20. Example output of ground-truth data through a cross-section and captured images of the trench (.png).

5.3. Experimental design, materials, and methods

Data were collected through a three-stage process: collecting metadata to describe the surveying conditions, collecting radargrams, and collecting ground-truth data. The following sections describe these stages' experimental design, materials, and methods.

5.3.1. Metadata

Metadata to describe the surveying conditions was captured through a combination of exploratory interviews and field observations. Before surveying, we organized interviews with one or two key actors from each construction project. These interviews, lasting approximately one hour, involved supervisors, project managers, and project clients. We asked them to explain their utility surveying objectives, expected outcomes, planned construction works, and distinctive characteristics of the surveying locations. Additionally, we acquired utility maps from these organizations, sourced through the Dutch national and regulated utility-data exchange platform (Dutch Cadastre Land Registry and Mapping Agency, 2022). These maps provided insights into the number and types of utilities present in the surveying areas.

Next, onsite surveying conditions were gathered. We compiled field notes through direct observations of the surveying areas, guided by insights from previous GPR studies (Ghanbari et al., 2022; Lai & Sham, 2023; Siu & Lai, 2019). These studies emphasized how soil types, groundwater levels, surface characteristics, and subsurface anomalies influence GPR output. The soil type observations were conducted after construction organizations excavated trenches. This allowed for a visual inspection of the type of soil. The ground relative permittivity values in the dataset were calculated after the observations. The velocity of GPR waves through the soil (v_m) was determined using the Reflex-W software's (version 9.1.3) hyperbola fit function. Using this velocity (v_m) and the speed of light (c), we calculated the ground relative permittivity (ε_r) through Equation 1.

$$\varepsilon_r = (\frac{c}{v_m})^2 \qquad [1]$$

Following the GPR surveying onsite, the GPR operator participated in discussions with the project teams, integrating his insights from the surveys with the construction expertise of the teams. Collectively, they determined the most suitable GPR method for achieving the specific surveying objectives at the construction site. This collaborative process resulted in a GPR method decision (i.e., standalone with post-processing, standalone without post-processing, or complementary alongside trenches) for each activity documented in the dataset.

Qualitative coding disseminated the interview and field note data toward the filtered metadata features. The principles of Corbin and Strauss (Corbin & Strauss, 2008) guided this process. First, open coding was used to code the data line-by-line.

Examples of codes include ‘replacement of utilities’ and ‘survey on the sidewalk’. Subsequently, axial coding was applied to link and group these codes into broader categories. These categories collectively constitute the features encapsulated in our metadata.

5.3.2. Radargrams

We employed an air-launched GPR featuring a 500MHz antenna complemented by Spectre’s SP80 GNSS (Global Navigation Satellite System) RTK (Real-Time Kinematic Positioning) receiver. This combination enabled the recording of subsurface objects’ geodetic locations in the x, y, and z axes. The air-launched design of the GPR resulted in the antenna being positioned just a few centimeters above the surface. This characteristic is visually evident within the radargrams, where the ‘airgap’ effect is discernible. In addition, the GPR was equipped with a measuring wheel encoder mechanism, enabling data transmission solely when the wheels were set in motion. The GPR used did not facilitate the collection of three-dimensional data.

Our GPR survey approach maintained a trace spacing of 0.02 meters, ensuring fine granularity. Per trace, 512 samples were recorded using a 50 ns time range. To manage and control the GPR system, we used a Panasonic ToughPad FZ-G1, which utilized proprietary software tailored to our GPR model. This tablet was the control hub, communicating with the GPR device via Bluetooth. A visual depiction of the experimental setup is presented in Figure 21.

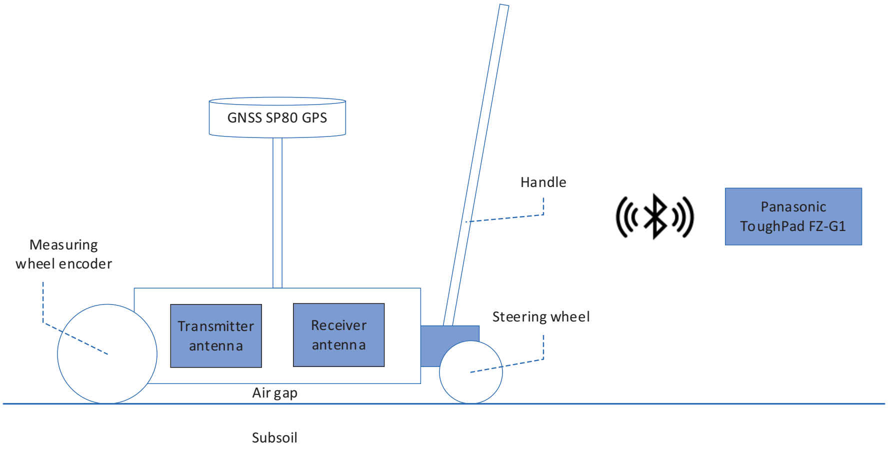


Figure 21. Schematic configuration of the GPR experimental setup.

GPR measurements were conducted at every location where the construction organizations had planned a trial trench. At these locations, survey lines were oriented perpendicular to the utilities. The emergence of a hyperbola in the radargram signified the crossing of a utility. Multiple survey lines were walked for each surveying activity to distinguish utility lines from potential anomalies. The range of survey lines varied from 2 to 26, generally spaced 1 meter apart – a suitable interval up to a busy urban setting (Institution of Civil Engineers, 2014). Survey lines were either separately collected or as one continuous trace in a 'zigzag' pattern depending on the available space to maneuver the GPR device. Examples of these two approaches are presented in Figure 22.

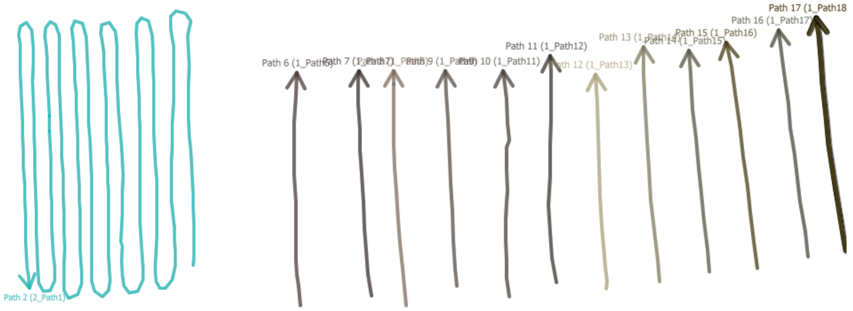


Figure 22. Continuous survey line (left side) and separate survey lines (right side).

The researcher walked the GPR along these survey lines to collect the radargrams. Data were hence collected at walking speeds. Employing the GNSS RTK receiver of the GPR, we could visualize the maps of the survey lines for each activity. However, in some surveying activities, tall buildings obstructed the GNSS signal. As a result, some measurements have inaccurate or missing mappings of the survey lines.

The radargrams were collected in the SEG-Y format. This is an open standard established by the Society of Exploration Geophysicists in 1975 (Barry et al., 1975). The format is the recommended archival file format for GPR data (Schmidt, 2013). The SEG-Y files in the dataset are unprocessed and in their raw state. They are directly imported from the GPR device.

5.3.3. Ground-truth

Ground-truth data were obtained through the excavation of trial trenches. The construction organizations themselves undertook this task. The digging process encompassed both manual and mechanical techniques. Guided by the utility maps at their disposal, workers dug these trial trenches to verify the utilities represented on the maps and pinpoint specific utilities or free (unoccupied) subsoil areas.

After the trenches were excavated, utility locations were determined. This process involved analog methods, including tape measures and water levels, or digital methods using GNSS technology. Analog approaches entailed recording the relative location and depth of utilities, while the GNSS technology facilitated the collection of geodetic coordinates in the x, y, and z axes. The construction organizations carried out or arranged the measurement procedures, with the added collection of utility discipline, material, and diameter types. Photographs were taken before the trenches were sealed. The visual depiction of a utility location recording, as witnessed in the surveying activities, can be found in Figure 23.

Figure 23. Use of digital GNSS technology (left side) and analog measures (right side) to determine utility locations.

Following the measurements, we acquired either cross-sectional data from the trial trenches or georeferenced CAD files supplied by the construction organizations. However, these CAD files are not enclosed in this dataset due to confidentiality constraints. Instead, the dataset contains cross sections or images of the exposed utilities, or a combination of these, for these files.

5.4. Limitations

The GPR and ground-truth dataset presents three limitations. First, several SEG-Y files within the dataset lack georeferencing information. While a GNSS RTK receiver was utilized for each GPR measurement, GNSS signal obstruction led to measurements only using the measuring wheel encoder. As a result, these SEG-Y files lack the geospatial context for the measurements.

Second, certain instances within the dataset feature GPR measurements in rough terrains, for example, ditches alongside roads. Such uneven and demanding topography led to instances where the measuring wheels could not maintain consistent ground contact. This compromised both the data throughput and its overall quality. Extracting information about subsurface utilities from the SEG-Y files in these cases becomes more challenging.

Third, the material and diameter type are not included for every utility in the dataset. Various construction organizations managed the collection of ground truth data, each adopting distinct approaches. This divergence resulted in instances where material and diameter details were omitted. In such situations, our ability to personally inspect the trial trench to collect this information was also limited, as trenches often had already been sealed due to safety considerations.

5.5. Specifications Table

Subject	Civil and Structural Engineering
Specific subject area	A realistic perspective on utility surveying with ground penetrating radar
Type of data	Raw radargrams in SEG-Y file format (.sgy). Processed images of survey line maps per activity in .png. Processed images of cross-sections of trial trenches in .png. Filtered metadata table describing the type of GPR application and site characteristics in .csv (one general file for all activities). Processed codebook table of metadata file in .pdf.
Data collection	Radargrams (.sgy) were collected using an air-coupled ground penetrating radar with a 500 MHz frequency antenna, a GNSS RTK receiver, and a measuring wheel encoder. A tablet using proprietary software was used to operate the GPR and visualize the radargrams. Ground-truth data (.png) were collected through trial trenching using analog and georeferenced measuring equipment. Metadata of the site (.csv) were collected through interviews, observations and conversations with the workers. The ground relative permittivity was calculated using the velocity of GPR waves determined through the hyperbola fit function in Reflex-W software (version 9.1.3).
Data source location	Data were collected across thirteen construction projects in the Netherlands located in or around Enschede, Eindhoven, Arnhem, Zwolle, Helmond, Helvoirt, Berkel-Enschot, Rotterdam, Zaandam, Oudewater and Feanwalden.
Data accessibility	Repository name: Ground Penetrating Radar dataset with ground-truth data of utility surveying activities Direct URL: https://data.4tu.nl/datasets/96303227-5886-41c9-8607-70fdd2cfe7c1 DOI: https://doi.org/10.4121/96303227-5886-41c9-8607-70fdd2cfe7c1.v1

5.6. Value of the data

- The intrinsic value of this dataset lies in its real-world origins. Unlike controlled or laboratory-based settings, this dataset is derived from authentic utility surveying activities. As such, it encapsulates the intricate complexities that subsurface utilities present in authentic scenarios.
- Encompassing 125 utility surveying activities, the dataset brings together information on how GPR was applied, a vast array of GPR radargrams – totaling 959 – and accompanying trial trench (ground-truth) data. This rich collection encapsulates an expansive set of utility surveying scenarios.
- The dataset's ground-truth foundation presents a unique opportunity for technology assessment experts to evaluate the capabilities of GPR across

an expansive array of authentic surveying conditions. Researchers can utilize this data to explore the practical value of GPR as a utility detection technology in the construction domain, aiding in identifying its use cases in realistic contexts of work.

- The raw radargrams in the dataset serve as a valuable resource for assessing and refining radargram processing algorithms and techniques. The diverse range of utility diameters, materials, and intricate complexities present in the dataset provides a dynamic testing ground. This testing environment allows researchers to scrutinize the efficacy of processing algorithms and determine optimal pathways for their evolution.
- By leveraging the dataset’s information on the type of GPR deployment for each of the 125 utility surveying activities, researchers can delve into the development of predictive models that anticipate the applicability of GPR in forthcoming surveying activities. Such predictive models empower practitioners with valuable insights into GPR’s anticipated value, enhancing the effectiveness of its onsite deployment.

Chapter 6

assessing machine learning-driven decision models for GPR-enhanced utility surveying

Assessing decision models that support ground penetrating radar-enhanced utility surveying

Abstract

Ground penetrating radar (GPR) is a non-intrusive technology for underground utility surveying. However, novice construction workers often lack the expertise to effectively determine which radar-based method to deploy onsite. This study assessed the expert-based and generalized machine learning methods of Case-Based Reasoning, Decision Trees, Random Forest, and Support Vector Machine to support their decision-making. We developed a training dataset by matching selected radar methods for 125 surveys with characteristics of sites with 28 encoded and different construction, geophysical, and infrastructural features. Using stratified k-fold sampling for training and assessing the model performances on 31 new decision cases using accuracy, F1, precision, and recall metrics, we found Case-Based Reasoning performing the best. This demonstrates the effectiveness of the expert-based model in supporting the onsite operational decision-making processes involving GPR, especially when training data is scarce. Future work should focus on assessing the models' scalability and exploring decision user interface options.

Keywords

Expert-based, decision-making, ground penetrating radar, machine learning, utility surveying.

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6.1. Introduction

The underground contains a dense network of utilities. Excavating here without proper surveying is a potentially dangerous undertaking. Surveying supports site exploration during the initial planning stages of construction projects. It helps to detect and localize cables and pipelines, in turn enabling the development of preliminary utility path designs and safe excavation measures (Thomas et al., 2009). Failing to conduct an effective survey can damage existing utilities, harm people in the vicinity, and lead to costly repairs (Jeong et al., 2004). For example, in 2022, around 47.000 excavation damages were reported in the Netherlands, adding up to over 38 million euros in repair costs (RDI, 2023).

One common practice of utility surveying is open-cut excavation (Racz, 2017; Ter Huurne et al., 2020), also referred to as ‘trial trenching’ or ‘trial pit digging.’ Workers making a trial trench dig up the ground to expose utilities and visually inspect them. While this method is highly accurate, it is also destructive, labor-intensive, provides only local insights into utility locations, and may cause damage by itself (Costello et al., 2007). Therefore, the alternative ‘trenchless’ method of ground penetrating radar (GPR) is increasingly considered (Costello et al., 2007; Lai et al., 2018; Metje et al., 2007). The GPR is a geophysical detection technology supporting a rapid, cost-effective, and minimally intrusive surveying procedure (Jol, 2009). It is applied to locate utility lines either as a standalone method or in complement to the traditional methods of trial trenching.

There are also limitations regarding the use of GPR. Unlike trial trenching, it is a specialized technology with inherent uncertainties. While non-intrusive, the technology can only detect underground utilities accurately for a limited set of physical conditions. For example, when utilities are buried in proximity, or when neighboring objects are closely located to a utility line, a GPR may not be able to distinguish a utility line from other objects. Further, soil type, moisture content, and density may obscure measurements (Costello et al., 2007; Jol, 2009; Metje et al., 2007). Hence, construction workers need both construction expertise and geophysical knowledge to choose which GPR method to deploy onsite.

However, due to the limited adoption of this technology currently, construction organizations often lack the necessary decision knowledge. Consequently, construction workers struggle to decide between three types of GPR methods: whether to use it as a standalone surveying method with post-processing radargrams, opt for a standalone method without post-processing radargrams, or employ it as a complementary method alongside trial trench verification. This situation currently leads to failures and ineffective applications of GPR for utility surveys (Lai et al., 2018).

Although studies attempted to reduce the uncertainties in GPR applications, they focus mostly on the processing of collected data rather than on how the technology needs to be deployed onsite. Examples of studies include generating visual aids to interpret radargram output uncertainties (S. Li et al., 2015) and automated methods for accurate depth analyses from measurements (Xie et al., 2021). While data processing advances gradually, knowledge about how GPR can be deployed onsite is less discussed in the literature (Lai et al., 2018). Moreover, fewer studies exist that aim to support operational decision-making on construction sites with automation methods (Xu et al., 2021). This study bridges that gap by developing machine learning-enhanced decision models for the GPR decision problem at hand.

Specifically, we aim to assess four decision-making models that support the problem of selecting between the three possible GPR deployment methods onsite. We developed and compared the effectiveness of the expert-based model of Case-Based Reasoning (CBR) and the generalized models of Decision Trees (DT), Random Forest (RF), and Support Vector Machine (SVM). As data for the decision problem under study was scarce, we trained the models with a newly developed dataset comprising solutions for 125 surveying decision problems. A comparison of the models' validation for 31 unseen expert decisions showed that CBR performed best. This signifies that expert-based decision models, such as CBR, may support onsite operational decision-making most effectively when limited training data is available.

The paper is structured as follows: We start by clarifying the site operational decision problem and providing motivation for selecting the decision models used in this study. Then, we outline the research methods to describe the steps taken to assess the four decision models. Next, we present the model assessments before discussing their performance and outlining potential directions for future research.

6.2. Literature and background

6.2.1. *The operational decision problem in GPR-enhanced utility surveying*

Ground penetrating radar (GPR) is a non-intrusive geophysical technology that supports subsurface investigation in civil engineering (Lai et al., 2018). It is particularly useful in situations where buried utilities cannot be easily accessed and located using traditional excavation-based methods. GPR can scan the subsurface in a minimally intrusive way to detect buried cables and pipelines. Essentially, it uses electromagnetic principles to detect and image utility infrastructure. The difference in dielectric constants of materials causes them to reflect radar waves differently (Jol, 2009). Once reflected, these waves (Figure 24a) are received by the GPR to make an image of the underground being surveyed. Anomalies are represented here through hyperbolas and may represent cross-sections of utilities (Figure 24b). From this radargram, one can deduce utility depth and, to a lesser extent, size and material.

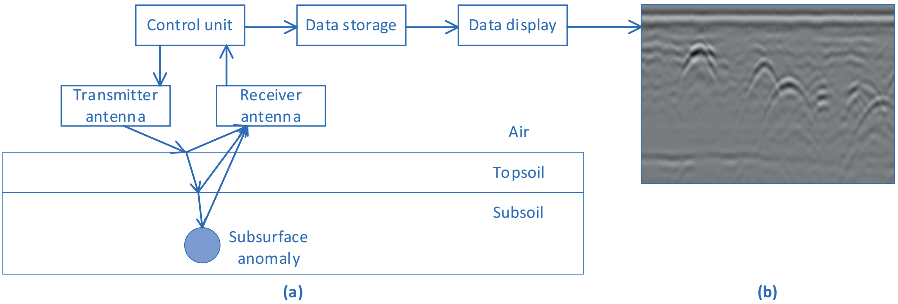

Figure 24. Schematic representation of GPR functioning (a), hyperbolas indicating utilities (b).

Despite its potential to enhance utility surveying practices, the deployment of GPR is often accompanied by uncertainties. While it performs optimally in dry soils with low electrical conductivity, it may encounter difficulties in areas with clayey soil types and high soil moisture contents, leading to reduced visibility of the objects being sought (Costello et al., 2007; Jol, 2009; Metje et al., 2008). Additionally, radargrams can become cluttered when buried objects, including utilities, tree roots, rocks, or other anomalies, create overlapping hyperbolic signatures, making it challenging to visually differentiate between them (Bai & Sinfield, 2020; Costello et al., 2007). This challenge is further compounded by the often limited insights into the as-built situation of utilities that construction organizations possess, as utility maps are often incomplete or inaccurate (Costello et al., 2007; Metje et al., 2007).

In addition to these uncertainties, a GPR's effectivity as a utility surveying method is also impacted by technical features. These include its antenna orientation, antenna frequency, and the tracing intervals set (i.e., the spacing between individual scan lines collected). Higher antenna frequencies and shorter tracing intervals increase the resolution of the radargram but decrease the penetration depth of the GPR's signal and slow down data collection, respectively (Utsi, 2017). Altogether, the consideration of the *geophysical*, *infrastructural*, and *technical* features within GPR applications is crucial when aligning them with utility surveying objectives. Such objectives may involve verifying the location of utilities on existing maps, localizing specific utility lines or appurtenances, and identifying safe 'free' underground areas for excavator operators. As a result, all these features collectively determine how GPR can be effectively deployed for a particular area on a construction site.

Three different GPR deployment methods can generally be identified: using it as a standalone surveying method with post-processing radargrams, as a standalone method without post-processing radargrams, or as a complementary method alongside trial trench verification (Institution of Civil Engineers, 2014; Ter Huurne et al., 2024). Using GPR as a standalone method means no other surveying methods are considered necessary for achieving the specified surveying objectives. It further distinguishes between using GPR as a standalone method with and without post-processing. Generally speaking, post-processing offers more detailed and accurate insights into the object locations found on the radargrams. Such higher accuracy may be necessary in conditions where a high number of utilities are expected to be found close to each other. In situations where less accuracy is required, for example, when only one major type of utility is, one may opt for using GPR as a standalone method without post-processing, as post-processing is labor-intensive and hence costly and time-consuming. If the GPR is unable to achieve the specified surveying objectives, it can still fulfill a complementary role alongside trial trenching. For example, GPR may help 'extrapolate' the local findings from trial trenches, assist in assigning locations for digging trial trenches, and aid in the search for undocumented utilities not present on utility maps.

Deciding when to deploy one of these three GPR methods requires a comprehensive understanding of the geophysical, infrastructural, technical, and construction-related features involved. We visualize this multifaceted decision-making process in a flowchart in Figure 25. When construction workers are tasked with making these onsite operational decisions, they often lack geophysical and technical expertise, hampering their ability to make well-informed decisions about the applicability of GPR. Under this decision problem, applications of GPR are prone to failure, as anticipated outcomes of GPR surveys may not align with their actual performance in practice (Lai et al., 2018).

This decision problem motivates the development of a decision model that provides a realistic outlook of the technology's operational effectiveness in real-life surveying contexts. The following section elaborates on the types of machine learning models that could prove valuable in this development process.

6.2.2. Machine learning classification opportunities

The utilization of machine learning has significantly changed the processes of decision-making in construction, as their applications offer construction workers access to intelligent types of decision support (Waqar, 2024). Especially since the construction sector is notorious for its resource planning, risk management and logistic issues, frequently leading to design flaws, project delays, cost overruns and contractual conflicts, the application of machine learning-based decision support has allowed for enhanced project outcomes, increased productivity, optimized allocation of resources, and early identification of potential risks (Kor et al., 2023). In contrast to conventional decision-making, relying on human expertise and intuition, machine learning-based decision models facilitate the expansion of construction workers' cognitive capabilities, allowing them to harness the potential of data-driven decision-making (Waqar, 2024).

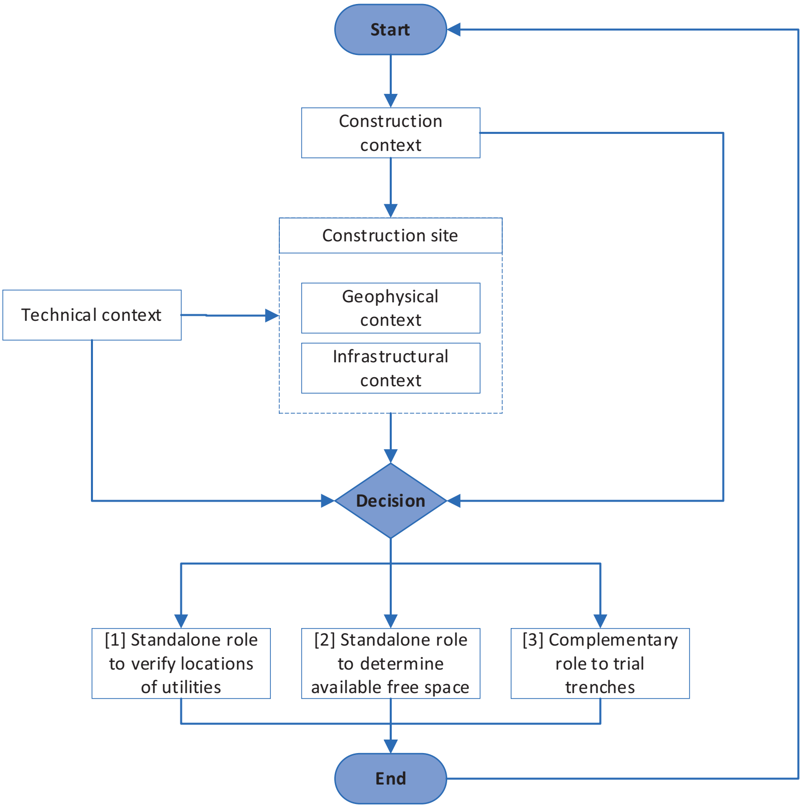

Figure 25. GPR decision problem flowchart.

In the GPR case of this study, machine learning solutions can help construction workers face the decision problem when deciding among three GPR method options. This type of decision is referred to as a *classification* problem. A classification model in machine learning is a type of algorithm that is trained to predict the category or class label of new observations based on past data. The goal of classification is to assign input data to one of a predefined set of classes (Kotsiantis, 2007). Generally, machine learning-based classification models tend to perform better with larger datasets. However, when data is scarce, generalized types of such models may be less reliable, as they rely on learning patterns directly from the data (Raudys & Jain, 1991; Vabalas et al., 2019; Varoquaux, 2018). In these scenarios, expert-based alternatives, which explicitly model knowledge by mimicking the expert reasoning process, can be more helpful (Hu et al., 2016).

Given the limited data available for the GPR decision problem, our paper hence assesses both expert-based and generalized models. Table 4 outlines the key features of the selected models, encompassing the expert-based Case Based Reasoning (CBR) model and the generalized models of Decision Trees (DT), Random

Forest (RF), and Support Vector Machine (SVM). Furthermore, the table includes examples of prior applications of these models in the construction domain.

Table 4. Descriptive summary of CBR, DT, RF and SVM for classification problems in construction.

Model	Features	Construction-related examples
Case Based Reasoning	Instance-based learning model; Stores and retrieves past problem-solving experiences (cases) to handle new ones; Easily interpretable.	Modeling of subcontractor registration decision (Ng & Luu, 2008). Modelling support for construction dispute settlement (Cheng et al., 2009). Formulating construction contract strategies (Chua & Loh, 2006). Developing a knowledge-based risk management tool (Okudan et al., 2021).
Decision Trees	Symbolic learning model; Uses a hierarchical structure of if-else rules; Handles missing values; Easily interpretable.	Modeling construction fall accidents involving roofers (Mistikoglu et al., 2015). Selecting a formwork method for tall reinforced concrete structures (Shin et al., 2012). Assessing the performance of water companies (Molinos-Senante et al., 2023). Selecting design parameters for one-way floor slab design (Fernandez-Ceniceros et al., 2013).
Random Forest	Ensemble learning model; Combines multiple decision trees; Handles high-dimensional data; Challenging to interpret.	Developing an automated-compliance-checking model for tunnelling strategies (Li et al., 2024). Predicting surface settlement levels in urban areas (Kim et al., 2022). Recognizing and tracking the activities of construction equipment (Langroodi et al., 2021). Detecting and classifying construction workers' loss of balance events (Antwi-Afari et al., 2018).
Support Vector Machine	Margin-based learning model; Uses hyperplanes to separate classes; Handles high-dimensional data; Challenging to interpret.	Classifying building elements for semantic integrity check of BIM (Koo et al., 2019). Retaining and utilizing experiential knowledge for construction problems (Cheng & Roy, 2010). Predicting potential disputes or construction claims during early planning phases (Chou et al., 2013). Classifying architectural style based on architectural design features (Strobbe et al., 2016).

Case Based Reasoning (CBR) is an instance-based learning model, also identified as an expert-based model due to its reliance on the expertise and experiences of human experts stored as past cases. Unlike the other machine learning models in this study, CBR does not build a traditional model during training. Instead, it defines past experiences as cases and utilizes similarity-based reasoning to classify future cases (Aamodt & Plaza, 1994; Hu et al., 2016). An often applied algorithm to calculate such similarity is *k-Nearest Neighbors* (kNN) (Kotsiantis, 2007). kNN is a non-parametric and instance-based supervised machine learning algorithm that calculates similarity by measuring the distance between data points in a multi-dimensional space. The distance is calculated between a new case and every other data point (i.e., historical cases) in the dataset. The CBR model in our study uses the *Euclidian* distance metric to do so. The Euclidean distance d_{AB} between two data points, A(x_{1A}, y_{1A}, ... z_{1A}) and B(x_{1B}, y_{1B}, ... z_{1B}) respectively, is calculated as follows:

$$d_{AB} = \sqrt{\sum_{i=1}^{n} (x_{iA} - x_{iB})^2}$$

The algorithm selects *k* data points (neighbors) with the shortest Euclidean distances to the query instance. These are the *nearest neighbors*. The new case is then assigned to the most common outcome among its *k* neighbors. This process is called *majority voting*. This local pattern recognition capability of CBR based on nearest neighbors is advantageous in scenarios where data scarcity is prevalent (Zhang, 2021). Further, the algorithm generalizes well and is interpretable and adaptable. The method has demonstrated its usefulness in addressing a range of construction decision problems, for example, in assessing and classifying subcontractors and their work categories (Ng & Luu, 2008) and providing risk-related knowledge to manage risks early on in the construction project (Okudan et al., 2021).

The other machine learning models in this study operate by generalizing from learned patterns. A Decision Trees (DT) is a supervised learning model that uses hierarchical structures of if-else rules to recursively split the data based on the feature that provides the best split, creating a top-down branching structure (Kotsiantis, 2007; Song & Lu, 2015). A decision tree typically comprises a root node that splits into multiple branches. Subsequently, a chain is established through the child nodes at successive levels of the tree. These child nodes are further subdivided into branches, and this process continues until an end node (leaf) is reached at the bottom of the tree. The distinctive path from the root to the leaf is defined as the decision rule (Mistikoglu et al., 2015). Therefore, the objective of a DT is to construct a model that forecasts the value of a target variable by learning decision rules derived from the data features. DTs are easily interpretable as the decision-making process can be visualized in the form of a tree (Kotsiantis, 2007; Song & Lu, 2015). Examples of the use of DT in construction automation are its use in supporting the selection of formwork methods for reinforced concrete structures

(Shin et al., 2012) and assessing the efficiency performance of water companies to determine future cost allowance and tariffs to customers (Molinos-Senante et al., 2023).

The best split at a root or child node is defined as one that does the best job at separating the data into groups where a single target class predominates in each group. This is referred to as the metric called *impurity* (Mistikoglu et al., 2015). A node is considered 100% impure when it is evenly split across the classes and 100% pure when all of its data belongs to one single class. When splitting, a DT seeks the lowest impurity of the new nodes, as this ultimately leads to a DT that can accurately classify instances. To define the impurity for a classification problem, one can use the *Gini Index* (Song & Lu, 2015). This index measures the probability of a random instance being misclassified when chosen randomly. The lower the index, the lower the likelihood of misclassification. For the Gini Index, a value of 0 corresponds to a pure node, while the maximum value of 0,5 corresponds to the highest impurity. Below is the formula for the Gini Index, where dataset *T* contains instances from *n* classes. In this formula, *p* is the probability of instances belonging to class *i* at a specific node.

$$Gini\ Index(T) = 1 - \sum_{i=1}^{n} (p_i)^2$$

The third type of machine learning model we assess in this study is Random Forest (RF). RF is a supervised learning model that utilizes multiple decision trees to make predictions. Each decision tree in the forest independently applies the splitting criteria based on an impurity metric, just like in a standalone decision tree algorithm. RF then combines their outputs to improve the overall performance of the model. It does so by introducing randomness into the process of building the decision trees in two main ways (Breiman, 2001). First, each decision tree in the forest is trained on a random subset of the training data. This process, called bootstrapping sampling, ensures that each tree sees a slightly different subset of the data. Within the decision trees themselves, RF further randomly selects a subset of features instead of considering all features to determine the best split. This helps in decorrelating the trees and making them more diverse. Therefore, RF aims to reduce overfitting and variance while maintaining or even improving predictive accuracy compared to a single DT. RF excels in handling high-dimensional data, managing noisy and correlated features, and estimating feature importance, which contributes to its robustness and effectiveness in classification tasks (Breiman, 2001). Recent use of RF in the construction automation domain includes the classification of surface settlement levels induced by urban tunneling (Kim et al., 2022) and the identification of geological conditions of excavation site and automated-compliance-checking for tunnel boring machines (Li et al., 2024).

Finally, SVM is a margin-based supervised learning model that finds optimal hyperplanes to separate classes in a high-dimensional feature space (Cortes &

Vapnik, 1995; Karamizadeh et al., 2014; Kotsiantis, 2007). A good separation is achieved by the hyper-plane that has the largest distance to the nearest training data points of any class (so-called functional margin), since, in general, the larger the margin, the lower the generalization error of the classifier. SMV models are effective for small sample sizes yet also handle high-dimensional data where the number of dimensions is greater than its samples. There are two types of SVM: linear SVM and non-linear SVM. Linear SVM is appropriate when the data is linearly separable, meaning that the dataset can be classified into multiple classes using straight lines (hyperplanes) only. Conversely, non-linear SVM is utilized when the dataset cannot be effectively separated using straight lines.

The choice of *kernel* in SVMs determines whether the SVM operates as a linear classifier or as a non-linear classifier (Cortes & Vapnik, 1995; Karamizadeh et al., 2014; Kotsiantis, 2007). Linear kernels are simpler and computationally less expensive, making them suitable for large-scale datasets or when the data is approximately linearly separable. Non-linear kernels, on the other hand, offer more flexibility and can capture complex relationships in the data. However, they may require more computational resources and can be more prone to overfitting if not properly tuned. The various kernel functions available in SVMs provide flexibility for addressing classification problems and capturing complex data relationships, enhancing the model's generalization capabilities. Examples of successful applications of SVM in construction include the classification of building elements to ensure the semantic integrity of building information models (Koo et al., 2019) and the classification of architectural styles (Strobbe et al., 2016).

Essentially, while the CBR, DT, RF, and SVM models may all support onsite operational decisions for GPR-enhanced utility surveying, it is unclear to date which machine learning model works most effectively. Following that, the study's primary aim is to assess these expert-based and generalized machine learning models for GRP-enhanced utility surveying.

6.3. Research methods

The applied machine learning process in our study comprised four sequential phases: [1] problem definition and data selection, [2] data preparation and preprocessing, [3] model development and training, and [4] model assessment. Figure 26 presents an overview of these four phases and their underlying steps. The following sections further elaborate on these.

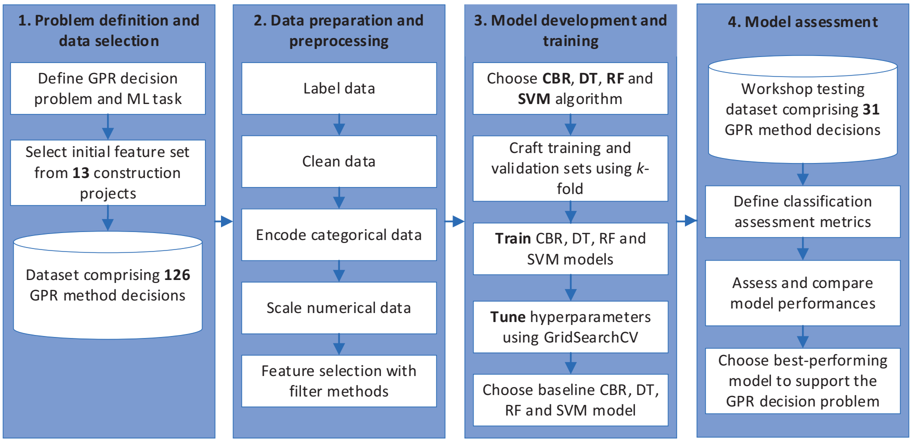

Figure 26. Overview of the applied machine learning process.

6.3.1. Problem definition and data selection

Our objective is to develop a machine learning model capable of predicting the ground penetrating radar (GPR) deployment method for utility surveying activities. The model aims to classify the GPR deployment method into one of three categories: GPR in a standalone role with post-processing (i.e., target class 0), GPR in a standalone role without post-processing (i.e., target class 1), and GPR in a complementary role to the method of trial trenching (i.e., target class 2). Our study's decision-making process is guided by the satisficing principle (Simon, 1957). According to this principle, decision-makers seek satisfactory solutions rather than aiming for optimal or perfect outcomes. In line with this, our decision model predicts GPR methods by analyzing historical data from successful GPR applications. Rather than employing a geophysical and technical optimal approach, our model relies on the features of past successful GPR method decisions. It utilizes these features to inform and guide decision-making for new cases.

Following this perspective, we developed a dataset comprising data from thirteen construction projects (Ter Huurne et al., 2024). The features collected were tailored to reflect what construction workers can feasibly obtain onsite in preparation for the surveying activity. The projects encompassed various settings, including inner-city areas, industrial zones, villages, and rural locations, and involved a wide range of activities such as sewage pipeline replacements, subsurface infrastructure reconstruction, installation of electricity lines, and fiber optic connections. Throughout these projects, we were involved in 125 surveying activities. For each activity, both GPR and trial trenches were used.

We collected construction, geophysical, infrastructural, and technical features. Construction features were obtained through interviews with project managers before the surveying activities. During these interviews, we inquired about survey objectives, required accuracy levels, the nature of planned construction works and whether there were precautionary warnings in place. Technical features pertain to the technical specifications of the GPR equipment utilized. Geophysical features were collected onsite during the surveying activities. These features included parameters like soil type and groundwater levels, determined through onsite inspection of trial trenches. Infrastructural features detailed the types of utility infrastructure found within the trenches, sourced from georeferenced maps provided by contractors after inspecting the trial trenches. In total, our initial dataset comprises 125 utility surveying activities, each represented by 26 features and a target feature as presented in Figure 28. Table 5 provides further information on these features and their values.

To collect the GPR method decision outcomes, the first author conducted GPR surveys and verified whether the GPR led to the survey information that the construction workers searched for. In total, he collected, labeled, analyzed, and pre-processed 125 utility surveys using a horizontally oriented 500 MHz air-coupled impulse GPR with a GNSS SP80 GPR receiver. The surveys involved walking along five to ten survey lines (traces) perpendicular to the expected utility line. Additionally, survey lines aligned with the infrastructure direction were walked to detect intersecting utilities (Figure 27, left side). The accuracy of the GPR survey outcomes was verified by comparing them with the ground-truth information obtained from trial trenches dug by the project teams (Figure 27, right side).

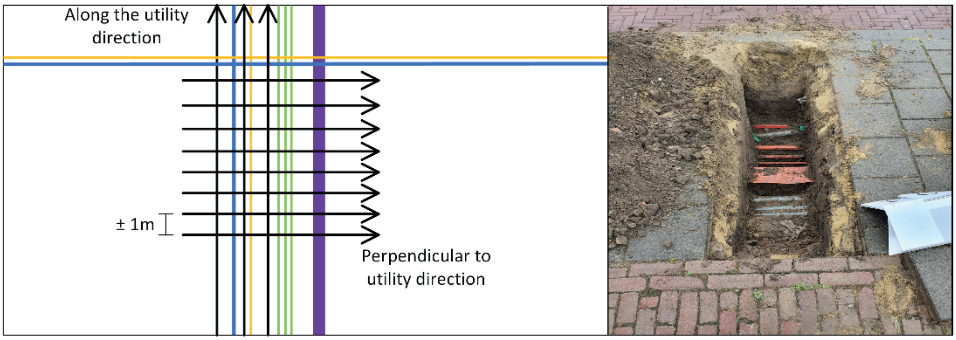

Figure 27. Illustration of survey lines at a surveying activity location.

After the surveying activities, the researcher engaged in discussions with the project teams, combining his insights from the surveys and the construction expertise of the teams. Together, they decided which of the three GPR methods had been the most effective at the specific construction site to achieve the surveying objectives at the site. For instance, at one site where workers had already excavated a trial trench, they sought to determine whether the visually identified cable extended beneath the street. Given that the required information needed low accuracy and the site's geophysical and infrastructural characteristics (sandy and dry soil with five utilities present) allowed for a scan without the need for post-processing, they selected "Class 0" as the most appropriate GPR method.

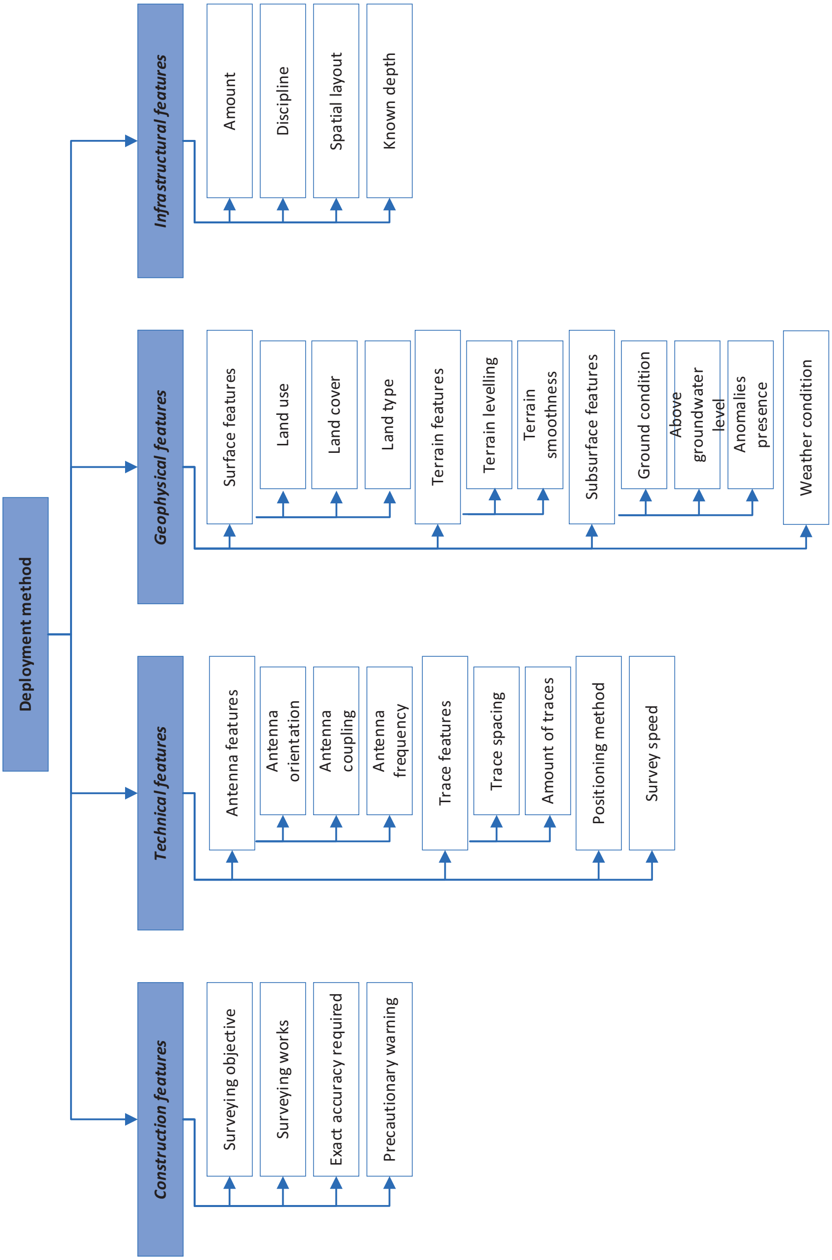

Figure 28. Dataset taxonomy for the GPR decision-problem.

Table 5. Initial feature set of GPR method decision-influencing features.

Category	Feature	Description	Values
Decision outcome	Deployment method	The chosen GPR deployment method for the surveying activity.	Standalone role with post-processing; Standalone role without post-processing; Complementary role to trial trenches.
Construction features	Surveying objective	The objective of the surveying activity, set by the project organizations.	Verify utility maps; Locate specific utilities/appurtenances; Map free subsoil space.
	Surveying works	The type works planned at the location of the surveying activity.	Replacement/remediation/installation of utilities; Excavation; None.
	Exact accuracy required	Whether project organizations require exact accuracy about the utilities' locations.	Yes; No.
	Precautionary warning	Whether a warning that project organizations receive when planning works near high-risk utilities is in place.	Yes; No.
Technical features	Antenna orientation	The positioning or alignment of the GPR antenna relative to the ground surface.	Horizontal; Vertical; Angular.
	Antenna coupling	The method by which the radar signal is transmitted and received by the GPR antenna.	Ground-coupled; Air-coupled.
	Antenna frequency	The frequency of the GPR antenna.	Integer value.
	Trace spacing	Spacing between adjacent traces during data collection, in meters.	Decimal value.
	Amount of traces	The amount of traces collected perpendicular to the orientation of the utility line per surveying activity.	Integer value.

Category	Feature	Description	Values
Technical features	Positioning method	Type of positioning system used to georeference the radar data.	Manual; GPS; Total station; Wheel positioning.
	Survey speed	The speed of dragging the GPR, in km/h.	Integer value.
Geophysical features	Land use	The type of land use at the site.	High-density residential; Commercial and industrial; Residential; Non-build up.
	Land cover	The material type of surface at the site.	Asphalt; Concrete tiling/bricks; Concrete slabs; Grass/vegetation; Rubble; Sand.
	Land type	The functional type of surface at the site.	Street/cycling road; Sidewalk; Pedestrian/parking area; Greenery; Construction site.
	Terrain leveling	Whether the terrain is flat or steep at the site.	Flat; Steep.
	Terrain smoothness	Whether the terrain is smooth or rough at the site.	Smooth; Rough.
	Ground condition	The type of soil that is found at the site.	Sandy; Clayey; Silty; Loamy.
	Above groundwater level	The relative level of the utilities to the groundwater level.	Yes; No.
	Anomalies presence	Whether and which type of anomalies are found at the site.	Rubble; Tree roots; Polluted soil; Blast furnace slag.
	Weather condition	Whether it is dry or rainy during the survey.	Dry; Rainy.
Infrastructural features	Amount of utilities	The amount of utilities found at the site.	Integer value.
	Discipline	The discipline of the utilities found at the site.	Electricity; Oil, gas, chemicals; Sewage; Water; Thermal; Telecommunications.

Category	Feature	Description	Values
Infrastructural features	Utility path linear	Whether utilities are laid out in a linear path at the site.	Yes; No.
	Utilities crossing	Whether utilities are crossing at the site.	Yes; No.
	Known depth	Whether the depth of the utilities is known prior to the survey.	Yes; No.

6.3.2. Data preparation and preprocessing

After having collected all features and the GPR method decisions, we formalized the data in a training dataset. This process included labeling, cleaning, encoding categorical data, scaling numerical data, and selecting relevant features using filter methods. Labeling the features of each scanned site and the matching GPR method decision, for example, meant we stored geophysical site features such as "sandy" for the ground condition and the integer value 5 to indicate the number of utilities at the location. We then cleaned the labeled dataset by handling missing values, outliers, and inconsistencies.

Next, we used one-hot encoding to transform the categorical features into a suitable format for the machine learning models. For example, the feature Soil type was encoded toward separate features for each value: 'SoilType: Sandy,' 'SoilType: Clayey,' 'SoilType: Silty.' and 'SoilType: Loamy.' We also scaled the original numerical features through normalization to ensure the numerical features were considered in the same scale range. Although tree-based algorithms like DT and RF are rather insensitive to different scale ranges, SVM and KNN are, hence our decision to include this step.

The subsequent feature selection process comprised two main steps. First, we removed features that met specific criteria: those with a single value, features showing high correlation with others, and features leading to spurious relations that hindered model performance. In the second step, we employed Chi-squared and Mutual Information filters to evaluate the importance of categorical and numeric features relative to the target feature, which had non-parametric distributions. After normalizing these scores, we ranked each feature based on the average of their Chi-squared and Mutual Information scores. Our choice of using filter methods over wrapper methods enabled a computationally efficient and less prone-to-overfitting approach for evaluating and comparing the machine learning models. We used this ranked list later in the machine learning process to determine one optimal feature all models.

6.3.3. *Model development and training*

We then proceeded with the development and training of the CBR, DT, RF, and SVM models. First, we split the dataset using the 125 surveying activities into training and validation samples using the *k*-fold cross-validation approach (Stone, 1974). We used a *k* value of five and used stratified sampling to provide the machine learning models with a balanced training dataset. Next, we implemented the classifiers by starting with a default hyperparameter set. We used Python packages as provided by the sci-kit-learn environment (Pedregosa et al., 2011).

For the CBR model, we implemented the *KNeighboursClassifier*. This classifier learns based on the k-nearest neighbor of each query point, where *k* is an integral number as defined by the user. The key hyperparameters used for the CBR model were the *metric*, which determined the type of distance metric used to calculate neighbor distances, and the n_neighbors, which determined the number of neighbors compared to a new instance. For the DT model, we employed the *DecisionTreeClassifier*. We included its *max_depth*, the *min_samples_leaf* and the *min_samples_split*. The max_depth parameter specifies the maximum levels allowed in each tree, while the min_samples_leaf determines the minimum number of samples required for a leaf node. The min_samples_split indicates the minimum number of samples needed to split an internal node. We used the *Gini Index* to measure the quality of the split and chose the *best* split at each node as a splitting strategy. The *DecisionTreeClassifier* uses an optimized version of the CART (Classification and Regression Trees) algorithm. For the RF model, we implemented the *RandomForestClassifier*. We included the same hyperparameters as the DT model complemented with the *n_estimators* hyperparameter. This parameter denotes the number of trees within the forest. Similar to our DT approach, the individual trees in the forest use the *Gini Index* and *best-split strategy* to do a split at each node. The classifier also uses the CART algorithm. Last, for the SVM model, we implemented the *SVC* classifier and used two hyperparameters: *C* and *kernel*. The *C* parameter determines the regularization strength, while the kernel parameter dictates the kernel type utilized in the model.

We trained each model using the initial feature set and then proceeded with tuning it. We used *GridSearchCV* to tune each model's hyperparameters. This algorithm requires a list of values to test for each hyperparameter, also called a parameter grid. The grids used for each model and its hyperparameters are presented in Table 6. The optimal combination of hyperparameters providing the highest accuracy when deployed on the training dataset set was chosen as the hyperparameter set.

Table 6. Parameter grid used for GridSearchCV.

Model	Hyperparameter	Parameter grid
CBR	metric	euclidean; manhattan; minkowski.
	n_neighbors	3; 4; 5; 6; 7; 8; 9; 10.
DT	max_depth	None; 5; 10; 20; 30.
	min_samples_leaf	1; 2; 4.
	min_samples_split	2; 5; 10.
RF	max_depth	None; 5; 10; 20; 30.
	min_samples_leaf	1; 2; 4.
	min_samples_split	2; 5; 10.
	n_estimators	50; 100; 200; 300
SVM	C	1; 10; 100.
	kernel	linear; rbf; sigmoid.

Using the tuned models, we iteratively removed the least important feature from the ranked list of features to identify the optimal feature set. Subsequently, we retrained, retuned, and assessed the performance of each decision model. This iterative process continued until the model performances either stabilized or declined. Our objective throughout this process was to achieve the best performance with the fewest features, facilitating practical implementation of the models in later stages. Ultimately, this phase concluded with finalized CBR, DT, RF, and SVM models.

6.3.4. Model assessment

To assess how well each of the models perform in predicting the three target classes, we made use of confusion matrices. Table 7 displays the types of matrix outcomes. TP1,2,3 represent the number of True Positives found. The E values represent the classification prediction errors. For example, the E01, 02 samples represent False Positives for Class 0, while the E10,20 samples represent the class's False Negatives.

Table 7. Outcomes of a confusion matrix for three-class classification.

		Predicted		
		Standalone GPR with post-processing: (Class 0)	Standalone GPR without post-processing : (Class 1)	Complementary GPR to verification: (Class 3)
True	Standalone GPR with post-processing: (Class 0)	TP_1	E_{10}	E_{20}
	Standalone GPR without post-processing : (Class 1)	E_{01}	TP_2	E_{21}
	Complementary GPR to verification: (Class 3)	E_{02}	E_{11}	TP_3

The outcomes of the confusion matrices were used to calculate four types of assessment metrics: accuracy, F1-score, precision, and recall. Accuracy measures the overall correctness of the model's predictions by considering true positives, true negatives, and all positive and negative observations (Eq. 1). We also calculate precision and recall and use the F1-score metric (Eq. 2). The F1-score takes into account both precision and recall. The precision metric is the proportion of positively predicted labels that are correct (Eq. 3). The recall metric, also known as sensitivity or the true positive rate, is defined as the ratio of true positives out of the actual positives (Eq. 4). We computed a weighted average of the precision and recall for each class. These, in turn, led to F1-scores as a balanced measure of the models' performances in both positive and negative instances. A comparison of these metrics per model helped us select the best-performing model for the GPR decision problem.

$$accuracy = \frac{TP+TN}{TP+FN+TN+FP} \qquad \text{(Eq. 1)}$$

$$F1 = 2 * \frac{precision * recall}{precision + recall} \qquad \text{(Eq. 2)}$$

$$precision = \frac{TP}{FP+TP} \qquad \text{(Eq. 3)}$$

$$recall = \frac{TP}{FN+TP} \qquad \text{(Eq. 4)}$$

We assessed and compared the performances of the developed decision models using these metrics. We compared the models' performances on the training and validation datasets to gain initial insights into their capabilities. To test the models' performance on unseen data, we organized a workshop involving eight experts who were experts in surveying and the use of GPR. They were asked to assign a GPR method to three construction sites that represented different decision problems. Based on the workshop technique called Nominal Group Technique (NGT) (McMillan et al., 2016), the experts collaboratively decided upon the appropriate target classes for the areas of the three simulated construction projects. Using rasterized maps, the experts made decisions based on relevant construction, geophysical, and infrastructural features, dividing the sites into appropriate target classes (Figure 29).

Figure 29. Experts deciding individually which target class to employ.

The workshop yielded one map per project, resulting in a total of 31 collectively agreed-upon GPR method decisions. These decisions comprised 12 cases where GPR was proposed as a standalone method with post-processing (i.e., target Class 0), 7 cases suggesting GPR as a standalone method without post-processing (i.e., target Class 1), and 12 cases recommending GPR as a complementary method to trial trench verification (i.e., target Class 2). The features depicted on each map, along with the 31 selected GPR methods, formed the ‘testing’ dataset for the workshop.

Subsequently, we assessed the models' performance on both the validation and testing datasets to facilitate comparison. This assessment helped determine which model best supported onsite operational decision-making for GPR-enhanced utility surveying. The findings from this assessment are detailed in the following section.

6.4. Results

This section describes and briefly analyzes the dataset used, then outlines the selected features for the model training, presents the optimized hyperparameters and assesses the decision models' performances.

6.4.1. Established training dataset

Table 8 presents the dataset used to train the decision models. During data processing, technical features were eliminated from the dataset since they remained consistent across all 125 surveying activities and did not contribute to the target outcome. Other features, such as land use and utility disciplines, were also removed due to their lack of predictive power or high correlation with other features. Additionally, the value 'blast furnace slag' for the feature 'anomalies' was removed as it was not present in the dataset. After one-hot encoding the features of Table 8, the dataset consisted of 25 categorical and 3 numerical features. Most categorical features are binary, while some possess multiple values, including surveying objective, surveying works, land cover, land use, and land type. The numerical features include ground relative permittivity, number of utilities, and density of utilities.

Table 8. List of GPR deployment method decision-influencing features.

Category	**Feature**	**Values**	**Type**
Construction features	Surveying objective	Verify utility maps; Locate specific utilities/appurtenances; Map free subsoil space.	Categorical
	Surveying works	Replacement/remediation/installation of utilities; Excavation; None.	Categorical
	Exact accuracy required	Yes; No.	Categorical
	Precautionary warning	Yes; No.	Categorical
Geophysical features	Land cover	Asphalt; Concrete tiling/bricks; Concrete slabs; Grass/vegetation; Rubble; Sand.	Categorical
	Land type	Street/cycling road; Sidewalk; Pedestrian/parking area; Greenery; Construction site.	Categorical
	Terrain leveling	Flat; Steep.	Categorical
	Terrain smoothness	Smooth; Rough.	Categorical
	Ground condition	Sandy; Clayey; Silty; Loamy.	Categorical
	Above groundwater level	Yes; No.	Categorical
	Anomalies presence	Rubble; Tree roots; Polluted soil; Blast furnace slag.	Categorical
	Weather condition	Dry; Rainy.	Categorical
Infrastructural features	Amount of utilities	Integer value.	Numerical
	Utilities crossing	Yes; No.	Categorical
	Utility path linear	Yes; No.	Categorical
	Known depth	Yes; No.	Categorical

Figure 30 shows the different types of distributions of the features. Most binary, non-binary categorical, and numerical features were skewed. From the 125 GPR deployment method outcomes that were determined when establishing the training dataset, the decision of choosing GPR as a standalone method with post-processing (i.e., target Class 0) was found 25 times; the decision of choosing GPR as a standalone method without post-processing (i.e., target Class 1) 12 times; and the decision of choosing GPR as a complementary method to support traditional trial trenching (i.e., target Class 2) 89 times. The GPR method decision distribution was hence skewed.

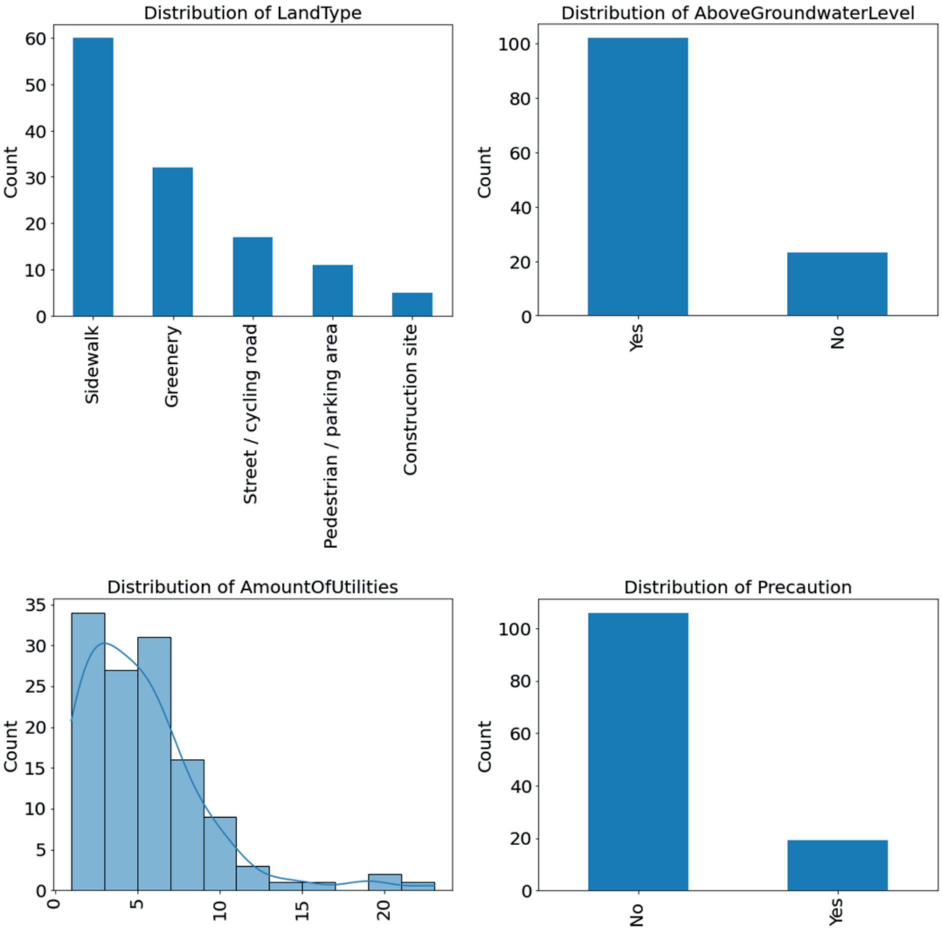

Figure 30. Four main distribution types of features in the training dataset.

6.4.2. Selected features

For the remaining features, Figure 31 plots and ranks the average feature scores based on the Chi-squared and Mutual Information filters. It shows the 'Objective: Map free subsoil space' (Feature 1) obtained a high score and had a significant contribution to the GPR method decision outcomes. 'Land Cover: Sand' (Feature 2) and 'Objective: Verify Utility maps' (Feature 3) also demonstrated strong relevance to the decision-making process. Conversely, 'Objective: Locate specific utilities/appurtenances' (Feature 20) and 'Exact accuracy required' (Feature 19) were the least relevant. From this ranked feature list, ultimately the first 13 features (starting from Feature 1) were selected as these yielded the best performances across the models during training and testing.

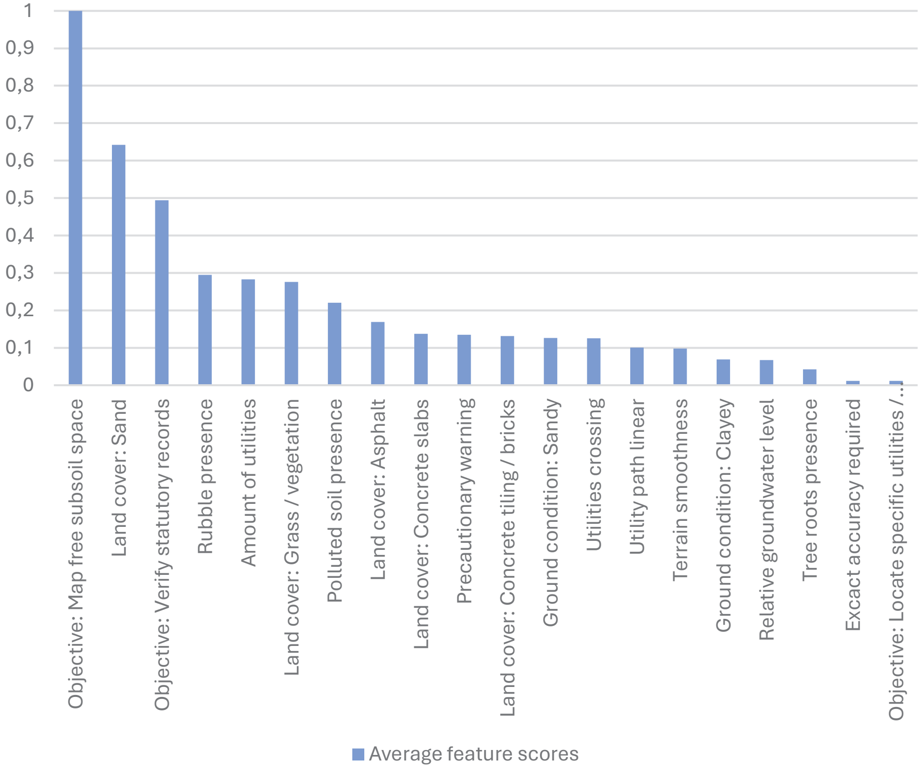

Figure 31. Bar graph displaying the average feature scores of Chi-squared and Mutual Information combined.

6.4.3. *Tuned hyperparameters*

Table 9 shows the optimal combination of hyperparameters after optimization. The values for each hyperparameter were derived from a final tuning iteration using the optimal feature set. Using these hyperparameters for each model yielded the best performances on the training and testing datasets. The performances of each model using these hyperparameters are further elaborated on in the next section.

Table 9. Optimal hyperparameter combination for each model.

CBR	metric: Euclidean	n_neighbors: 5		
DT	max_depth: 5	min_samples_leaf: 1	min_samples_split: 5	
RF	max_depth: 5	min_samples_leaf: 2	min_samples_split: 5	n_estimators: 100
SVM	C: 100	kernel: rbf		

6.4.4. *Assessed models*

Figure 32 presents the combined results of the confusion matrices obtained for each of the five folds on the training dataset. The models showcase overall good performance, with few occurrences of false positives. The CBR, RF, and SVM models have 12, 13, and 12 false positives, respectively. The DT model performs slightly less accurately, with 19 false positives. Further, Class 1 (i.e., the standalone method of GPR without post-processing) consistently has the least false positives, while Class 0 (i.e., the standalone method of GPR with post-processing) shows a higher ratio of false positives to total instances. The latter suggests Class 0 is harder to predict.

Figure 33 presents the confusion matrices for validating the model performances on the workshop validation dataset (the unseen dataset). Here, CBR shows the highest accuracy, with only 4 false positives. SVM counted 6 false positives. Both the RF and DT models had 11 and 13 incorrect classifications, respectively. All models misclassify 4 out of the 12 instances for Class 2 (i.e., the GPR method complementing trial trench verification).

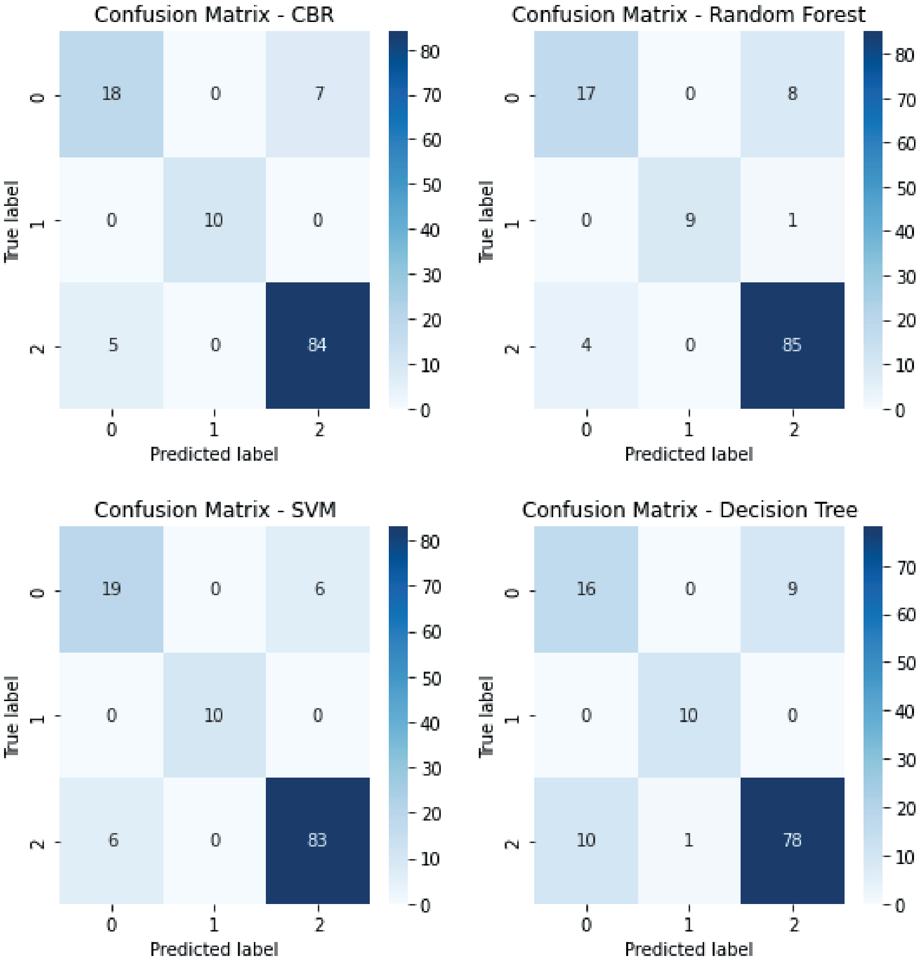

Figure 32. Confusion matrices per k-fold for the CBR, DT, RF and SVM models on the training dataset with; Class 0: GPR as a standalone method with post-processing, Class 1: GPR as a standalone method without post-processing, and Class 2: GPR as a complementary method to trial trench verification.

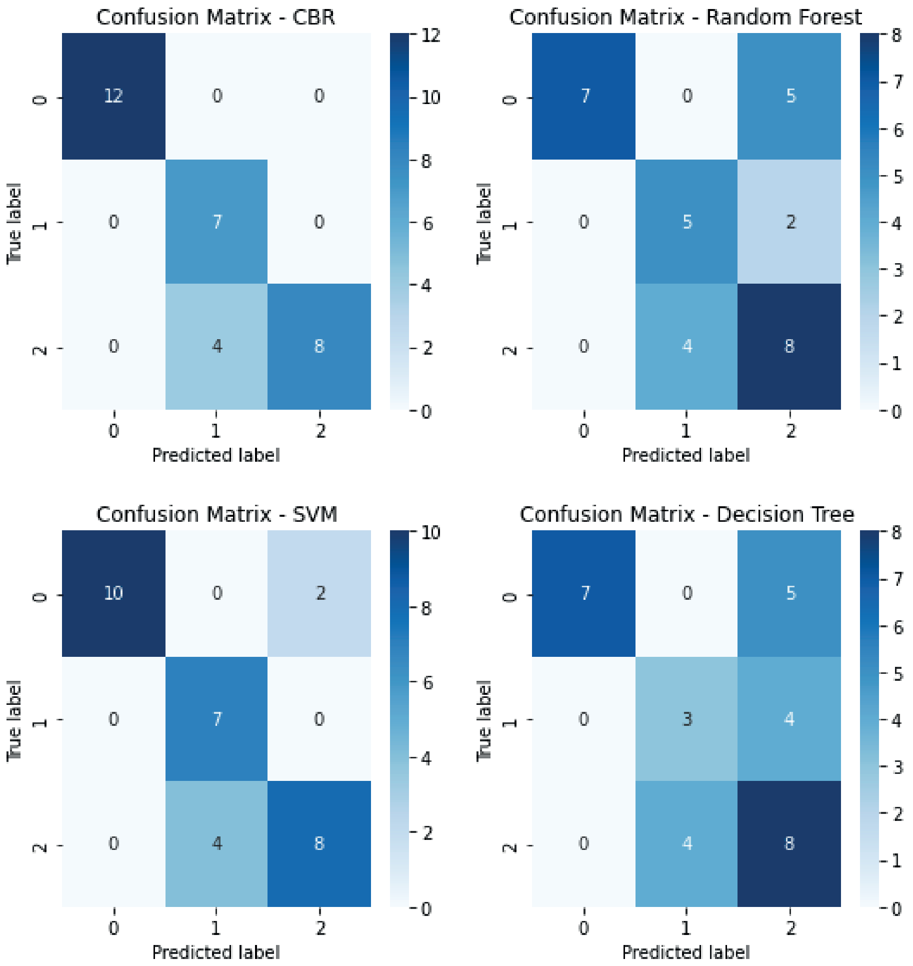

Figure 33. Confusion matrices for CBR, RF, SVM and DT models for the workshop validation dataset with; Class 0: GPR as a standalone method with post-processing, Class 1: GPR as a standalone method without post-processing, and Class 2: GPR as a complementary method to trial trench verification.

A comparison of the metrics in Figure 34 shows that the model outcomes based on the workshop validation dataset had a higher number of false positives compared to the outputted solutions from the training dataset. The CBR, RF, and SVM models demonstrate strong performances on the training dataset, with similar accuracy and F1-scores. Further, the Decision Tree scores lowest but still provides reasonable classification results with an accuracy of 0.839 and an F1-score of 0.839.

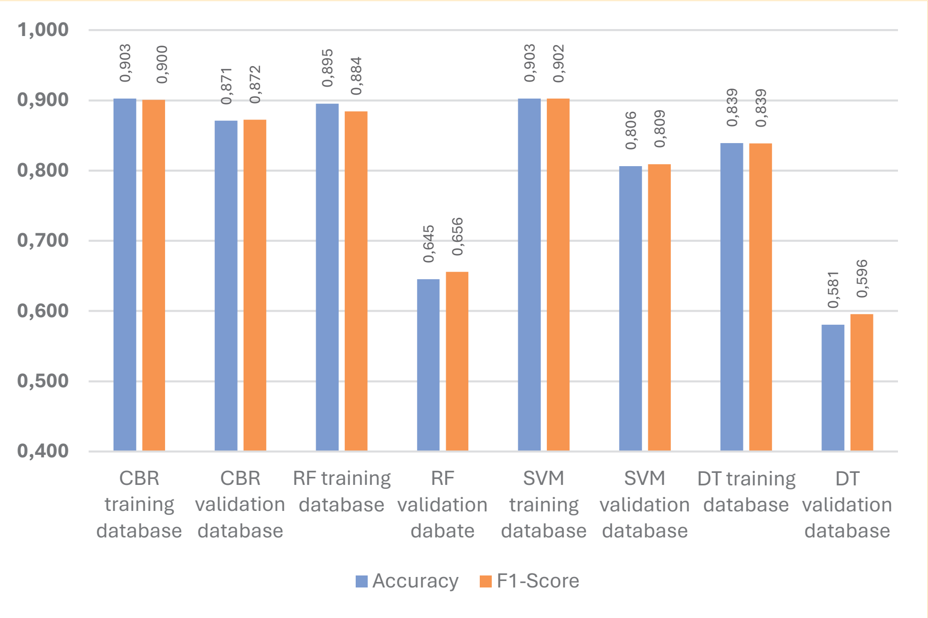

Figure 34. Accuracy and F1-scores for the models on the training and workshop validation dataset.

Assessment of the models based on the outputs after applying the decision models on the workshop validation dataset, shows that only the CBR and SVM models exhibit strong performances. The CBR model emerges as the top performer, having an accuracy of 0.871 and an F1-score of 0.872, which is only slightly lower than its performance on the training dataset. The SVM model also demonstrates good performances, although slightly lower than the CBR model. In contrast, the RF model experiences a significant decrease in performance on the workshop validation dataset, while the DT model exhibits the weakest performance.

Essentially, the assessment of the models on both the training and workshop validation dataset demonstrates that the expert-based CBR model outperforms the generalized models of DT, RF and SVM. This finding gains further support when assessing the precision, recall, and F1-scores of each model per target class, as presented in Table 10. Notably, the table shows that the CBR model consistently delivered the strongest performances across all target classes and decision models. Specifically, it achieved perfect precision, recall, and F1-scores for Class 0 (i.e., the standalone method of GPR with post-processing) and Class 1 (i.e., the standalone method of GPR without post-processing). Additionally, the CBR model demonstrated the best overall performance in Class 2 (i.e., the GPR method complementing trial trench verification).

Table 10. Precision, recall and F1-score per class for each model on the workshop validation dataset.

Class	Model	Precision	Recall	F1-score	Support
0	CBR	1.000	1.000	1.000	12
0	Random Forest	0.583	1.000	0.583	12
0	SVM	0.833	1.000	0.833	12
0	Decision Tree	0.583	1.000	0.583	12
1	CBR	1.000	0.636	1.000	7
1	Random Forest	0.714	0.556	0.714	7
1	SVM	1.000	0.636	1.000	7
1	Decision Tree	0.429	0.429	0.429	7
2	CBR	0.667	1.000	0.667	12
2	Random Forest	0.667	0.533	0.667	12
2	SVM	0.667	0.800	0.667	12
2	Decision Tree	0.667	0.471	0.667	12

6.5. Discussion

This study assessed the effectivity of the expert-based Case Based Reasoning (CBR) model and the generalized models of Decision Trees (DT), Random Forest (RF), and Support Vector Machine (SVM) in supporting onsite operational decision-making of GPR-enhanced utility surveying. This contributes to the literature in two ways.

First, our study demonstrates the effectiveness of expert-based decision models, specifically CBR, in supporting the experience-driven onsite operational decision-making processes involving GPR. Out of the four decision models we assessed, the CBR model, using the k-Nearest Neighbors (kNN) algorithm, emerged as the most successful, outperforming the generalized DT, RF, and SVM models in terms of accuracy and F1-scores. Our workshop validation data simulated the use of the models once confronted with unseen data from real-life practices and revealed that the CBR model achieved the strongest classification performances with an accuracy of 0.871 and an F1-score of 0.872. Similar modeling problems in the literature also benefit from CBR's learning performance, showing that the model excels at utilizing past cases and similarity measures to predict new situations (Aamodt & Plaza, 1994; Hu et al., 2016; Kolodner, 1992). We, therewith, contribute a new empirical case regarding automated decision support; and, reaffirm CBR's capacity to capture intricate real-world decision problems in construction (Chua & Loh, 2006; Ng & Luu, 2008; Xu et al., 2018).

This study, therewith, is one of the few to compare expert-based and generalized decision models for an empirical construction decision problem. While expected that methods including DT, RF (Breiman, 2001; Kotsiantis, 2007), and SVM (Cortes & Vapnik, 1995) may be used as generalized solutions, these models encountered challenges in capturing class-specific patterns, leading to the lower performance scores demonstrated in this study. This finding emphasizes that context-based onsite operational issues relying on expert knowledge may still best benefit from a model that explicitly captures such knowledge. This leads to the second contribution.

Second, the results contribute the insight to the literature that expert-based decision models, such as CBR, can deliver strong classification performances when empirical training data is scarce. While previous research emphasizes the sensitivity of machine learning classifiers to sample sizes, with larger datasets generally yielding more accurate predictions and lower error rates (Raudys & Jain, 1991; Varoquaux, 2018), our findings emphasize the potential of leveraging smaller datasets (i.e., a dataset comprising 125 instances as in this study) to effectively support onsite operational decision-making. While classification biases can persist even with up to a thousand training instances (Varoquaux, 2018), we show that expert-based models like CBR may nevertheless be effective for construction cases including onsite operational decision-making. These findings may extend beyond GPR method selection, where knowledge can be explicated to build expert-based models but where data scarcity poses a challenge for the decision problem to be supported.

This study's limitations also lead to recommendations for future research. For one, we recommend assessing the scalability of onsite operational decision models as more data becomes available (Raudys & Jain, 1991; Varoquaux, 2018). Although it is hard to collect larger and more diverse datasets for the onsite operational decision-making problem of GPR, it may be fruitful to investigate conditions when generalized models perform satisfactorily. Furthermore, we recommend exploring how decision user interfaces will further support the site adoption of decision models. Spatial Decision Support Systems (SDSS) seem a viable option for this purpose. SDSS are geographical tools designed to assist decision-makers in solving spatially related decision problems by combining spatial and non-spatial data to conduct spatial analyses, visualize spatial maps, and predict decision outcomes (Keenan & Jankowski, 2019; Ruiz et al., 2012; Ruiz & Fernández, 2009). Incorporating a decision model in an SDSS could automate the feeding of input data (feature information from utility maps, soil maps, and groundwater level records), visualize decision outcomes, and, therefore, support construction workers in their onsite decision-making processes.

Finally, we outline the practical contribution of this study, which is introducing a GPR-enhanced utility surveying decision model. By guiding construction organizations on the onsite operational use of GPR, this model could help facilitate onsite decision-making, in turn enabling the broader implementation of GPR in the construction context (Lai et al., 2018). This may provide better insights into the utilities' whereabouts and enhance safety in construction practices.

6.6. Conclusions

This study assessed the effectiveness of the expert-based Case-Based Reasoning (CBR) and generalized Decision Trees (DT), Random Forest (RF) and Support Vector Machine (SVM) decision models in supporting onsite operational decision-making for GPR-enhanced utility surveying. Training of the models occurred based on a developed training dataset comprising 125 unique surveying cases. We used a stratified 5-fold cross-validation process during training and validated the models using 31 unseen expert decisions. The results demonstrated that CBR outperformed the other generalized models, correctly predicting 27 instances and achieving an overall accuracy and F1-score of 0.87.

These findings contribute to the literature with the insight that expert-based decision models, such as CBR, effectively support the onsite operational GPR decision problem. This experience-driven operational decision-making problem is typical for construction and may inform the development of other operational decision models in the sector. Second, the findings demonstrate that expert-based models like CBR can outperform generalized models like DT, RF, and SVM when dealing with limited empirical training data. Future research is suggested to look further into identifying when generalized models are sufficiently provided with rich data to surpass the performance of expert-based models and exploring the merit of a Spatial Decision Support System (SDSS) in supporting the adoption of decision models onsite.

Ultimately, we call for using expert-based models in other construction contexts where data scarcity challenges decision-making regarding the use of technologies. Just as in this study with GPR, these models can potentially promote the use and adoption of new construction technologies. Such technologies ultimately make a practical contribution, allowing construction organizations to perform tasks like GPR surveys more effectively and leading to safer construction practices.

Chapter 7

prior and complementary research work

7. Prior and complementary research work

The five preceding chapters form the core of the research efforts undertaken to accomplish the primary objective of this dissertation. In addition, I worked on complementary research projects. This chapter provides an outline of these complementary endeavors through four sections. Particularly, section 7.1 delves into the challenges of digitization within the fragmented construction sector. Section 7.2 provides a summary of how the concept of ontologies can offer assistance in such fragmented contexts. Section 7.3 presents previous work on utilizing computer-aided tools for assessing the risk of utility strikes. Section 7.4 describes systemic barriers to the adoption of GPR. This chapter concludes by presenting the key conclusions of the complementary work.

7.1. Digitization amid fragmentation

In my first study[1] in the domain of subsurface utilities, I argued how implementing digital practices may lead to digital information but not necessarily to a common and accepted set of digital practices. The construction industry increasingly digitizes the life cycle of construction assets by defining concepts, attributes, and their relations. This digitization of reality often takes form by creating virtual counterparts in environments like Building Information Modelling (BIM) and Geospatial Information Systems (GIS). Digitization is further supported by the rapid development of technologies like artificial intelligence (AI), big data, the Internet of Things (IoT), cloud computing, wireless sensor networks, and the fifth-generation cellular network (5G). Altogether, these digital advancements propel state-of-the-art engineering and problem-solving in the construction industry.

A common belief within the construction field is that digitizing asset lifecycle information enhances stakeholder collaboration. This argument is built on the assumption that by uniformly adopting one knowledge base for their software, stakeholders can decrease ambiguity and increase the consistency of exchanged information. Nonetheless, unquestioningly assuming this notion could lead to what is known as 'digitization hubris.'

The problem with this optimistic view that digitization stimulates integration is that it ignores that digital practices themselves are also fragmented. The complexity of software interoperability and the integration of information further complicates the endeavor to integrate these fragmented practices. According to Turk (2001), standardized data formats and structures contribute to achieving integration, provided they are accepted and accurately reflect practitioners' collective understanding of reality.

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[1] ter Huurne, R.B.A., Olde Scholtenhuis, L.L., and Dorée, A.G. (2018). Digitization for Integration: Fragmented realities in the utility sector. In: Gorse, C., and Neilson, C.J. (Eds.), *Proceedings 34th Annual ARCOM Conference: Working Papers*, Belfast, UK, 92-100.

Conversely, the absence of uniformity in adopting standards and the lack of consensus hinder achieving seamless integration. The latter has given rise to a phenomenon referred to by Timmermans and Epstein (2010) as “a world of standards, but not a standard world.” This phenomenon is also typical for construction, where nations, organizations, and even individuals have been formulating digital standards in a rather fragmented and self-centered manner (Azhar, 2011).

In the study, I postulated the hypothesis that digitization of the construction asset life cycle does not automatically lead to the integration of stakeholders and more collaborative work practices. To investigate this hypothesis, I explored whether such a unified and accepted standard existed for the utility sector and examined whether the ongoing digitization endeavors yielded consistent digital practices. In particular, I identified the knowledge bases – data standards and modeling protocols for engineering software – that twelve distinctive subsurface infrastructure owners use. Two utility taxonomies from the literature were used to compare the identified digital modeling standards. Subsequently, I drew upon literature about modeling standards in digital practices to elucidate how selected examples of divergent digital models hamper uniformity.

During the study, I discovered that modeled digital realities employed by the subsurface infrastructure owners were embodied within: (1) global, (2) national, and (3) organizational standards. The study revealed that each utility owner prescribed their own standard for asset data registration, reflecting their distinct operational methods. It shows that organizational standards were more frequently employed than their international and national counterparts. While the various organizational standards encompass similar objects and attributes, I found that their ‘standardization’ follows unique trajectories. A selection of examples in the study illustrates differences in the representation of domain knowledge. They emphasize how elicited digital realities differ in the use of taxonomy, vocabulary, and semantics.

This existence of diverging realities confirms that the utility sector lacks a uniform digital modeling practice. This, in turn, limits the possibilities for IT developers to align information systems that uniformly exchange utility data between network operators and contractors. The study, therewith, emphasizes that institutional initiatives aimed at stimulating digital collaboration should be cautious in assuming that digitization supports integration. Instead, the study stresses the relevance of defining shared domain understanding to facilitate the uptake of digital models for collaborative engineering practices. Particularly, professional paradigms are urged to develop standards that capture ‘shared ontological understandings.’

A subsequent research project showcased the development of such shared ontological understandings. Ontologies have the potential to bridge any varieties that may exist between distinct knowledge bases and their subsequent data models. They depict the worldview of a particular group at a given point in time according to a particular perspective grounded in a set of core propositions or ideologies (El-Diraby & Osman, 2011). An ontology can be defined as a formal and explicit outline of shared conceptualizations (Staab & Studer, 2009). Conceptualization refers to the universe of discourse. Shared refers to an ontology's capacity to accommodate multiple viewpoints. The terms 'formal' and 'explicit' highlight that the concepts encapsulated in the ontology must be presented in a distinct, machine-interpretable format. Once adopted and shared among practitioners, ontologies function as tools to represent knowledge in a unified, simplified, and consistent way.

This subsequent study[2] explains that when representing knowledge through ontologies, careful consideration of phenomenology - a philosophical branch that deals with how to take things for what they are and what it means 'to be' – and hermeneutics – a philosophical branch focusing on interpretation – is required. These roles of intention and interpretation are pivotal when capturing realities through ontologies, as their connotations can be shaped by both their creators and users. Ontologies, hence, require achieving consensus among domain professionals about the captured intent and interpretation of the knowledge it represents.

The study highlights how, through an engaged ontology development process, an ontology was developed to represent utilities (detailed in section 7.2). This engaged approach involved close collaboration with potential end-users and the industry to achieve consensus. The study illustrates how concepts were derived from the participants' distinct knowledge bases and industry standards. This process unfolded over a series of more than twenty industry meetings. By integrating a diverse range of assessment criteria and subjecting the ontology to a partial field test within a utility asset management context, the research concluded that the ontology was comprehensive and appropriately aligned with its intended design context and application domain.

The findings emphasize that the co-development of an ontology with domain professionals facilitated the emergence of a shared conceptualization of the domain. The processes stimulated a behavior of seeking consensus, which aided in aligning diverging realities. The approach forms a strong foundation for creating interchangeable digital models. Consequently, this engaged ontology development could be crucial in bridging fragmented realities within digital and virtual construction environments. This is especially relevant in the current era of construction digitization, where the rapid growth of digital models such as digital twins is prevalent.

[2] Ter Huurne, R.B.A., Olde Scholtenhuis, L.L., and Dorée, A.G. (2022). Engaged Ontology Development to Bridge Fragmented Digital Realities. In: Tutesigensi, A and Neilson, C J (Eds.), *Proceedings 38th Annual ARCOM Conference*, Glasgow, UK, 328-337.

7.2. Developing an ontology to model utilities

Developing the previously mentioned ontology was a component of my Engineering Doctorate (EngD). The ontology's contents are further elaborated upon in a study[3] submitted to a Dutch conference and the EngD dissertation[4]. Essentially, the motivation behind creating the ontology stemmed from lacking a digital modeling standard for utilities. Specifically, there is an absence of a standard emphasizing lifecycle management, i.e., operations and maintenance. As the utility sector is shifting toward a life-cycle-oriented management approach, utility owners increasingly want to have comprehensive digital information about their utilities. They need uniform and consistent digital information about these utilities.

A digital modeling standard was required to avoid confusion and misunderstandings when exchanging information during the planning and execution of utility-related tasks. Departing from this problem statement, an ontology was developed to encompass the fundamental concepts and relationships associated with utilities' operations and maintenance phases. Given that the ontology was designed with a specific emphasis on conceptualizing knowledge in this specific realm, it was termed a 'domain ontology' throughout the work.

To organize the ontology development process, I employed Wieringa's engineering cycle (2014), including four distinct phases: (1) problem exploration, (2) design, (3) validation, and (4) implementation. Focusing on the ontology's design phase within the engineering cycle, a design methodology was formulated that adhered to the following stages: framing competency questions, outlining the ontology's requirements, selecting suitable ontology development tools and languages, and developing the ontology itself. As discussed earlier, engaged development was employed throughout this design phase.

To affirm that the developed ontology encapsulated the essential domain knowledge, I employed four validation techniques: (1) comparison against a domain data source, (2) check against class modeling rules, (3) evaluation based on input from an expert panel, and (4) evaluation against posed competency questions. After validation, the ontology was successfully implemented in a GIS environment as a proof of concept. A subsequent examination extended the testing of the ontology by employing a spatial-relational database containing maintenance data (Fossatti et al., 2020).

[3] Ter Huurne, R.B.A. (2018), Introductie van een uniform objectmodel voor het beheer en onderhoud van ondergrondse infrastructuur. *CROW Infradagen 2018*, Arnhem, Netherlands.

[4] Ter Huurne, R.B.A. (2019). *Modelling utilities by developing a domain ontology*. [EngD thesis, University of Twente]. University of Twente.

To facilitate ease of access, the ontology, comprehensive documentation, and associated data have been made accessible through an online repository[5]. This repository enables potential users to freely access all essential resources for implementing and utilizing the ontology.

So far, adopting the ontology within the (Dutch) utility sector remains challenging. Although the ontology is employed within the University of Twente to model their utilities, its potential in enhancing system interoperability for utility data has not been fully realized. This opens the door to exciting research opportunities, particularly in examining the macro dynamics of adopting such a sector-wide innovation. Such an investigation would necessitate a comprehensive understanding of the institutional, organizational, and operational contexts that collectively shape this innovation landscape.

7.3. Discrepancies between human and computer-aided risk analysis

Beyond the development of ontologies, the uptake of digitization initiatives within the construction industry also creates opportunities to utilize computer-based tools to support risk management processes. This dissertation itself presents an example of such a tool in the form of a decision model developed to aid construction practitioners in selecting effective GPR deployment methods. Additionally, in parallel to this dissertation, I explored the efficacy of a utility strike risk assessment tool[6] in a study submitted to an international construction management conference. This tool assists workers in identifying locations for the excavation of trial trenches.

To mitigate utility strikes and their associated negative consequences, accurate and comprehensive data about the locations and attributes of utilities are required. To gather this data, exposing utilities via trial trenches to visually inspect the buried utilities is then typically applied. However, since trial trenches only provide local information at the excavation point, decision-makers must strategically determine where to position these trenches while constrained by budget and time. This necessitates that decision-makers possess a comprehensive understanding of the associated risks of having a utility strike. Coupled with the inherent uncertainty surrounding utility locations, the potential for human error introduces the possibility of suboptimal decision-making.

[5] Ter Huurne, R.B.A. (2019). *Utilities – Operations and Maintenance conceptual schema*. GitHub. https://github.com/RamonTerHuurne/UtilityNetwork-OperationsAndMaintenance

[6] Ter Huurne, R.B.A. (2021). The Role of Risk Attitudes: Discrepancies Between Human and Computer-Based Risk Analysis in the Utility Sector. In: Scott, L, and Neilson, C.J. (Eds.), *Proceedings 37th Annual ARCOM Conference*, UK, 844 853.

As part of their risk attitude, decision-makers typically rely on their intuition, judgment, and expertise. Given the often-limited precise information or knowledge of risks accessible to decision-makers – a phenomenon referred to as bounded rationality (Simon, 1997) – inconsistencies and vagueness in the risk management process can result in suboptimal decision-making. Consequently, computer-based tools emerge as advantageous in this context. They possess the capability to navigate through dynamic and uncertain environments.

Despite their evident theoretical advantages, the utilization of computer-based tools remains underutilized in the context of uncertainty-driven utility locating practices. Following this notion, the study aimed to assess how effectively the risk of utility strikes is currently managed without computer-based tools. Subsequently, I compared the locations chosen through human decision-making for three Dutch construction projects with the locations suggested by a pre-developed utility strike risk analysis tool (Racz, 2017). This computer-based tool calculates the risk level for a potential utility strike on a given construction site and provides recommendations for locating trial trenches based on the calculated risk level. The findings revealed that the locations of trenches chosen through human decision-making lacked a clear and predefined logic. When compared to the locations recommended by the computer-based tool, the study highlighted two key points:

- Human decision-making results in a significantly lower number of locations being considered for investigation compared to the computer-based tool;
- The trial trench locations chosen by human decision-makers often do not correspond to areas where the risk of excavation damage is most significant.

Upon investigating these differences, I discovered the root cause to be a difference in the motivation behind digging trial trenches. Specifically, the primary motivation for trenching within the studied projects was to verify the initial designs of new utilities. These designs were cross-referenced with the layout of buried cables and pipes onsite to verify the plan's feasibility. This current risk approach only partially contributes to the utility sector's aim of reducing excavation damages.

Economic incentives prevail, likely influenced by the construction industry's fragmented and project-centric nature. While computer-based tools have the potential to assist in determining trial trench locations, a shift in risk perception within the industry is a prerequisite. The study urges the industry to reassess its risk management approach. It proposes that the institutional framework should channel efforts toward fostering a culture of careful excavation within the utility surveying practice community.

7.4. Systemic barriers to GPR adoption

Ground penetrating radar (GPR) is considered a solution that can help promote careful excavation practices. Despite its potential, the technology's use on construction sites remains low (Lai et al. 2018). While many studies focus on enhancing GPR's utility detection capabilities from a technological perspective (Ghanbari et al. 2022; Siu & Lai 2019), there is a lack of understanding about why its adoption in the utility sector neither significantly scales up nor completely phases out. To complement the practice-based micro-level studies of Chapters 3 and 4 of this dissertation, it is essential to understand the broader socio-technical system in which GPR is introduced. To date, studies that explore the adoption of GPR from such a systemic, socio-technical perspective are missing.

In a study[7] I submitted to an international construction management conference, I explored why GPR has not become a common alternative to trial trenches in the Netherlands. I did so by uncovering systemic barriers through a socio-technical systems perspective. This perspective considers technological factors and the social and institutional dynamics surrounding GPR's introduction. In particular, I employed the Technological Innovation System (TIS) framework by Bergek (2019). By identifying the systemic barriers hindering the adoption of GPR through this framework, the study provided insights for scholars and policymakers, helping to develop comprehensive strategies to overcome these barriers and facilitate the broader adoption of GPR within the utility sector.

The TIS analysis followed three main steps. First, a structural approach defined the innovation system in terms of actors, networks, and institutions affecting or potentially affected by GPR's introduction (Bergek 2019). Second, a functional approach explained the system's dynamic performance using seven system functions (SF) as defined by Hekkert and Negro (2009). Each system function represents an abstract category of activities affecting technology development: (SF1) entrepreneurial activities, (SF2) knowledge development, (SF3) knowledge diffusion, (SF4) guidance of the search, (SF5) market formation, (SF6) resource mobilization, and (SF7) creation of legitimacy. The assumption is that a sufficient presence and smooth interaction between all functions result in an innovation system where the technology can successfully develop and diffuse.

In the third and final step, I determined the causality between the various activities related to the system functions. This step identified three cycles of interdependent systemic barriers sustaining a lack of GPR adoption within the Dutch utility sector:

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[7] Ter Huurne, R.B.A., and Coenen, T.J.C. (2024) [forthcoming]. Exploring the Barriers of Ground Penetrating Radar Adoption: A Technological Innovation System Analysis. *Proceedings 40th Annual ARCOM Conference*, London, UK.

the knowledge cycle, the institutionalization cycle, and the misalignment cycle. These cycles are visualized in Figure 35, which highlights the most apparent barriers contributing to them.

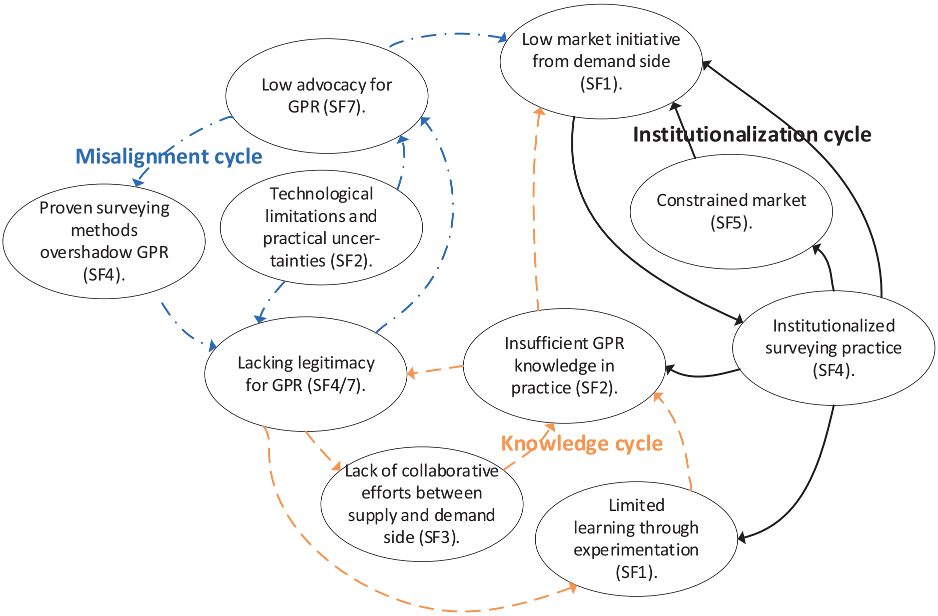

Figure 35. Three cycles of systemic lock-ins to the adoption of GPR in the Dutch utility sector.

The knowledge cycle sustains insufficient knowledge in practice regarding implementing and using GPR (SF2). Insufficient knowledge about GPR's capabilities and limitations persists as the Dutch utility sector exhibits limited learning through experimenting with GPR (SF1). Little collaborative effort exists between the demand and supply sides, resulting in limited knowledge diffusion (SF3). This lack of knowledge undermines the legitimacy of GPR as a surveying approach (SF7), sustaining the observed knowledge barrier.

The institutionalization cycle sustains the institutionalized surveying practice that excludes GPR. Institutionalized surveying practices steer the demand side away from experimenting with GPR (SF1) and developing knowledge about its use (SF2), favoring proven methods. Economic incentives within project-based surveying activities prioritize short-term gains over safety and comprehensive surveying practices. These constraints prevent the market from developing supportive niches for adopting GPR (SF5), allowing current surveying practices to persist.

The misalignment cycle sustains the lack of legitimacy for GPR (SF7). Despite the urgency to reduce excavation damages and increase productivity, little legitimacy is created for GPR technology. Proven surveying methods overshadow GPR (SF4) due to low advocacy for GPR in the sector (SF7). Technological limitations and practical uncertainties associated with GPR also deter its consideration as a viable option.

In my exploration of why GPR technology has not become a common alternative to trial trenches, I found that the three cycles of insufficient knowledge, lack of legitimacy, and institutionalized surveying practices are interrelated and fuel each other. Insufficient knowledge on the demand side undermines GPR's legitimacy as a surveying method. This lack of legitimacy, in turn, prevents organizations from experimenting with the technology and developing knowledge about its use. Simultaneously, the absence of knowledge and legitimacy sustains institutionalized surveying practices and the lack of market initiative from the demand side, altogether hindering GPR adoption.

To facilitate GPR's adoption, I advocate for increasing awareness and understanding of GPR among industry professionals and policymakers. Recommendations include developing and evaluating educational and training programs focused on GPR usage and implementing and evaluating pilot projects that demonstrate GPR's effectiveness in utility surveying, as discussed throughout this dissertation. Furthermore, fostering a supportive regulatory environment for GPR adoption is crucial. Initiatives could begin by positioning GPR as a viable option within directives on surveying.

7.5. Conclusions of complementary work

The summarized complementary research endeavors outlined above may not form a seamlessly integrated whole. Nevertheless, they address four prevalent challenges in the ongoing digitization and digitalization efforts in the Dutch utility sector: navigating a highly fragmented digital landscape, establishing shared ontological conceptualizations, transitioning toward increased use of computer-aided tools for utility strike prevention, and overcoming systemic lock-ins that inhibit the adoption of innovative solutions like GPR. The resulting conclusions from these complementary research endeavors are as follows:

- Despite digitization's anticipated role in stakeholder integration and software coherence, fragmented realities in the utility sector impede uniform digital models. This poses challenges for aligning information systems between network operators and contractors. A shared domain understanding is vital for collaborative digital engineering practices;

- Ontologies have the potential to bridge fragmented digital realities. An engaged ontology development approach helps foster consensus among domain professionals, which is essential for establishing a shared set of conceptualizations of the domain;
- Computer-aided tools offer the construction industry the potential to support utility strike prevention by effectively determining trial trench locations. Achieving this, however, demands a shift in risk attitude since the current motivations behind trenching do not appear to align with the industry's goal of reducing utility strikes;
- The limited adoption of GPR in the Dutch utility sector is primarily due to systemic issues: insufficient knowledge, lack of legitimacy, and entrenched institutional practices. These factors create interrelated cycles that hinder the technology's acceptance and use. Increasing awareness and understanding through education, pilot projects, and supportive regulatory frameworks is essential to overcome these barriers.

Overall, the complementary research presented in this chapter provides a blend of technical and socio-technical insights. It offers a broader perspective on current digitization and digitalization efforts in the Dutch utility sector. It enhances the practice-based micro-level insights from this dissertation by providing a systemic outlook on the barriers to GPR adoption. Together with Chapters 2-6, this complementary work informs the discussions and conclusions described in the next two chapters.

Chapter 8

discussion

8. Discussion

This chapter starts by outlining the dissertation's main theoretical contributions and practical implications. Subsequently, I reflect upon the research methods and concepts employed during this PhD research and conclude with recommendations for future research.

8.1. Theoretical contributions

The central objective of this dissertation is to explore and support GPR-enhanced utility surveying practices. To achieve this, I adopted Orlikowski's (2000) lens of technology-in-practice, which provided a perspective for developing context-rich socio-technical insights into the actual use of GPR on construction sites. The construction management literature emphasizes that context-rich, practice-based studies of innovation such as these are necessary to develop deeper understandings of a technology's impact and contributions (Harty, 2008; Shibeika & Harty, 2015). Studies of predecessors like Paavola and Miettenin (2018) and Van den Berg et al. (2021) also embraced context in their studies of early adopters using Building Information Modeling technology. This PhD research, however, addresses a different type of case, namely not that of a widespread technology, but a contested, emerging technology that is in a pre-adoption phase. This led to three main theoretical contributions.

First, this dissertation provides a practice-based understanding of the early interactions between emerging technology and its prospective users. This helps determine in which situations the technology can be used effectively and where it cannot. Specifically, section 8.1.1 reflects on how the lenses of routine dynamics and Cultural Historical Activity Theory (CHAT) help reveal the dynamic relation between evolving practices and GPR technology in early-stage innovation phases. Second, uncovering early innovation adoption dynamics in the situated context of technology use requires a bespoke, engaged research approach. Section 8.1.2 outlines, based on the context of GPR, how a participatory take on formative interventions supports such an approach. It details five action types for researchers to build theories of change. Third, the lack of insight into the operational value of the GPR for construction workers complicated its use onsite. This study gained context-rich socio-technical insights into the actual use of GPR, thereby enabling the development of a decision support model for GPR-enhanced utility surveying. Section 8.1.3 elaborates how this knowledge was captured in an expert system that uses machine learning to support operational decisions about GPR onsite.

8.1.1. Conceptualization of early-stage innovation adoption dynamics

This dissertation contributes to the innovation literature by providing extensive empirical evidence that practice-based studies allow for the detailed conceptualization of how early innovation adoption processes are shaped in local practice. Specifically, Chapters 3 and 4 employed Orlikowski's (2000) technology-in-practice perspective to examine the use of emerging technology in situated contexts. These chapters offer empirically rich examples of early-stage interactions between technology and individuals through the case of GPR.

Chapter 3 examines how local practices adapt to emerging technologies by analyzing routine dynamics, focusing on the interaction between guiding thoughts (ostensive aspects) and actual actions (performative aspects) (Feldman, 2000; Pentland & Feldman, 2005). It identifies two change triggers: disruptions, where routines produce unexpected results, and shortcomings, where routines fail to meet expectations. These triggers influence practitioners to consider new technologies like GPR when current practices fall short, while stability is maintained when practices work as expected or when new technologies perform poorly. The chapter contributes an empirically grounded model that clarifies how routines change or stabilize and aids decision-makers in evaluating the receptiveness of existing practices to emerging technologies. This model enriches construction management literature by showing how early change triggers can lead to reevaluating established routines and stimulate the exploration of new technologies, providing insights into how established practices can both facilitate and hinder innovation adoption in construction.

Similarly, Chapter 4 scrutinizes early adoption dynamics from an activity-theoretical perspective, emphasizing how interactions between users and technology lead to new integrations within activity systems. Using Engeström's (2015) Cultural-Historical Activity Theory (CHAT) framework, the chapter demonstrates that the recognition of GPR technology's value in resolving contradictions – fundamental conflicts or tensions within an activity system – has transformed existing surveying practices. The analysis identifies three types of activity systems: verifying documented utilities, searching for undocumented or crossing utilities, and designating subsoil free space. GPR technology was integrated into these systems in various ways: as a complement to trial trenching, as a supporting tool, and as a substitute. This illustrates the diverse ways in which the technology can be incorporated into future practices. Building on prior research on construction technology implementation (e.g., Hartmann et al., 2012; Lines & Reddy Vardireddy, 2017; Lundberg et al., 2019), the chapter shows that technology implementations do not simply replace existing ideas or practices but can drive transformations by addressing (previously overlooked) contradictions.

Altogether, Chapters 3 and 4 contribute to a grounded understanding of two key benefits of doing contextualized studies of early-stage (technological) innovations. The first benefit relates to societal impact. By positioning technology in context, prospective users can immediately explore it within their everyday practices, facilitating learning and knowledge development. Technology use is strongly influenced by users' understanding of its properties and functionality (Orlikowski, 2000). As potential users oftentimes lack familiarity with an innovation or are misinformed about its use (Sepasgozar et al., 2021), direct experiences with emerging technologies like GPR in practical settings create awareness, technological know-how, and shape their motivations toward its use (Swanson & Ramiller, 2004). These immediate experiences prompt users to reassess their existing practice and develop a meaningful understanding of the value of technology as a solution to existing problems that have yet to be resolved. In the terminology of Rogers' (2003) innovation diffusion process, this process primarily allowed for the development of awareness knowledge – i.e. knowing about the technology – and how-to knowledge – gaining initial insights into its use within existing practices.

The second benefit involves exploring diverse enactments of technology-in-practice. This PhD study's practice-based approach, which involved practitioners as co-creators of knowledge, revealed the flexibility in using emerging technologies. To better understand how innovations in construction practices are brought about, such a contextual approach allows us to study innovation as a flexible idea, explored through the situated and local implications of these practices (Orlikowski, 2000). This theoretical notion implies that the use of an innovation is always 'contextualized' (Gambatese & Hallowell, 2011). Such an approach is particularly valuable in the construction industry's complex socio-technical landscape, where emerging technologies' enactment varies across different settings. This variability is shaped by the diverse intentions and practices of individuals (Ninan et al., 2022), which significantly influences how innovations are adopted and adapted within the industry's varied contexts (Harty, 2008; Shibeika & Harty, 2015). Consequently, this PhD dissertation emphasizes that technology use should be viewed as a situated process of development rather than a fixed set of predefined features. The case study of GPR illustrates how this perspective can uncover the benefits of lesser-understood innovations in construction practices.

To this end, this dissertation articulates that conceptualizations of early-stage innovation dynamics through practice-based studies allow for developing an understanding of how emerging technology may change operational and organizational processes before formal adoption takes place. Such early understanding can help construction organizations better navigate the potential disruptions and challenges often associated with technology implementation (Heidenreich & Talke, 2020; Lines & Reddy Vardireddy, 2017). This proactive insight can prevent 'implementation failures' (Klaus & Blanton, 2010) and streamline more mindful innovation.

8.1.2. Methodological adaptation for emerging technology studies

This dissertation contributes to the understanding of how to study early innovation dynamics of emerging technologies in construction practices. It highlights the necessity of a bespoke methodological approach. Unlike widespread technologies, emerging technologies such as GPR have not yet become embedded in current organizational practices (Pink, 2022; Rotolo et al., 2015). This presents unique challenges for researchers. Traditional 'distanced' research methods – such as observations and interviews – are insufficient for studying these technologies due to their uncertain impacts and lack of integration into existing practices. Instead, this dissertation proposes an 'active' interventionist approach as an alternative methodology. Chapter 4 illustrates through the case of GPR how participatory, interventionist methods can uncover early innovation dynamics that would otherwise remain hidden.

In particular, the chapter outlines a participatory take on the method of formative interventions. While formative intervention approaches from CHAT – involving the deliberate activity by researchers within an activity system to provoke and drive a transformation process among practitioners (Sannino, 2011; Sannino et al., 2016) – have been applied in the construction management literature to study the impact of widespread technologies like BIM (e.g., Mäki and Kerosuo 2015, Akintola *et al.* 2020), their use in cases of emerging technologies has been limited. By immersing a researcher-interventionist in practice-based studies of emerging technology, this dissertation demonstrates how researchers can use interventions to stimulate practitioners' engagement in learning and transformation processes effectively. Such immersive learning encourages the exploration of new perspectives, ideas, and approaches among practitioners regarding their practice and use of technology. This approach fosters a context for developing rich, context-specific insights into various technology-in-practice enactments. These insights help clarify the emerging technology's future, rather than given, impact and role.

This bespoke application of formative interventions allows research interventionists to become internal participants in the activity system. This immersion challenges the conventional assumption that transformation processes must be led and owned solely by practitioners (Sannino et al., 2016) and contributes to the CHAT literature by demonstrating that the researcher interventionist can also cross the 'boundary' of concrete practice – an idea articulated by Engeström (1995) to describe individuals stepping outside their usual roles, i.e., the distanced role of the researcher. Researchers can do so while still respecting practitioners' freedom to interpret their actions and envision new ways of acting (Van Oers, 2013). The argument here is that 'participating' does not necessarily entail directing how transformation unfolds, but when interpreted in a richer way, enhances both researchers' facilitating capabilities while preserving practitioners' transformative agency.

Researchers can use this renewed take on formative interventions to develop theories of change using the methodological principles underpinning the CHAT interventionist approach: *double stimulation* and *moving from the abstract to the concrete* (Engeström et al., 2014). This dissertation contributes five specific actions for researcher interventionists to develop such theories of change in studies of emerging technology:

1. Actively shape conditions for emerging technology consideration;
2. Expose tensions to help actors identify manifestations of contradictions;
3. Assist actors in resolving these contradictions;
4. Operate as tool operators to guide actors in exploring the emerging technology, and;
5. Facilitate reflection among actors on existing activity system elements.

Building on the principles of engaged scholarship (Van de Ven, 2007), these five action types enable researchers to actively intervene and co-create knowledge with practitioners as internal participants. Informed by previous research on engaged scholarship in construction management research (Voordijk & Adriaanse, 2016), this produces three types of knowledge: *knowledge about action* (explanations and theorization of actions in local practice), *knowledge for action* (proposals for improving practice with emerging technology), and *knowledge through action* (exploring new ways of working with emerging technology). Together, these knowledge types provide a deeper insight into the dynamics of local practice and its potential for transformation. This participatory take on formative interventions, therewith, enriches the ongoing discourse on the role of the engaged scholar in interventionist research (Engeström et al., 2022). It frames the world as one in motion rather than a static state, highlighting that while the transformative agency of learners is central to this movement, the engaged scholar can play a crucial role in facilitating and supporting this dynamic process.

8.1.3. Integration of expert knowledge in machine learning

This dissertation contributes to the construction automation literature by advocating for the integration of expert knowledge with machine learning. One of the primary challenges in machine learning is the availability of data. Achieving high-accuracy models typically requires a substantial amount of data, which can be difficult, expensive, or impractical to obtain (Deng et al., 2020). Specifically in construction, site environments are often complex and heterogeneous, complicating the collection of data and performance of machine learning models (Xu et al., 2021). These challenges are particularly significant when developing decision support for the use of emerging technology in construction practices. Little data is typically available regarding the practical use of these technologies. This dissertation highlights the benefits of incorporating domain-specific human expertise to overcome these obstacles.

Chapter 6 demonstrates that expert-based decision models can effectively capture intricate real-world decision problems, using the 125 GPR deployment strategies outlined in Chapter 5 as input. These strategies were developed through close collaboration with construction domain experts, encapsulating their expert knowledge in selecting the optimal strategy for each utility surveying activity. Among the four decision models assessed in Chapter 6, the expert-based Case-Based Reasoning (CBR) model, using the k-Nearest Neighbors (kNN) algorithm, emerged as the most effective. It outperformed the generalized decision tree (DT), Random Forest (RF), and Support Vector Machine (SVM) models in terms of accuracy and F1-scores. The findings showed that CBR excels at utilizing past cases and similarity measures to predict new situations. Aligning with prior research (Chua & Loh, 2006; Ng & Luu, 2008; Xu et al., 2018), this dissertation underscores CBR's capacity to effectively capture intricate real-world decision problems by reasoning similarly to humans, suggesting that practice-based onsite decision problems may still best benefit from expert-based machine learning models.

Furthermore, the findings demonstrate that integrating expert knowledge into models like CBR can achieve high accuracy even with modest amounts of training data. This was illustrated by successful predictions in utility surveying tasks with just 125 instances. To this end, the dissertation contributes to the construction automation literature by showing that the integration of human expertise alongside empirical data in machine learning frameworks promotes a more nuanced and effective approach to developing automated solutions tailored to distinct operational contexts. These findings may extend beyond GPR method selection to other construction contexts where data scarcity challenges the decision problem to be supported.

8.2. Practical implications

The practical motivation to explore and support GPR-enhanced utility surveying stems from ongoing transitions in energy, climate, and green initiatives. These have intensified the demand for work near approximately 1.7 million kilometers of underground cables and pipelines in the Netherlands. Compounded by pressing labor shortages, there is an increasing need to accomplish more work with fewer people, often under the pressure of completing tasks "as quickly and cost-effectively as possible," as emphasized by practitioners during one of the projects visited, while aiming to prevent utility strikes.

The geophysical GPR method is expected to enhance productivity during utility surveying practices and help reduce utility strikes. However, the insufficient understanding among construction practitioners of when, where, and how to deploy GPR, has resulted in failed applications and limited adoption. This dissertation contributes practical knowledge and operational decision support that have two main implications for practice. First, the findings from this dissertation sketch a broader application domain for GPR. In section 8.2.1, I elaborate on the previously unexplored applications for GPR. Second, the integration of the GPR decision model developed faces technical and systemic hurdles. In section 8.2.2, I elaborate on these hurdles from the perspective of the Dutch utility sector.

8.2.1. Broadened applications for GPR

Through the development of socio-technical insights into how GPR impacts and contributes to surveying practices (Chapters 3 and 4), three potential uses for GPR in utility surveying activities have been identified: as a *complementary*, *supporting*, or *substituting* tool for the traditional combination of utility maps and trial trenching. Until now, both scholars and practitioners have primarily focused on the use of GPR to locate utilities accurately and comprehensively, corresponding to its substituting role. In a substituting role, GPR replaces trial trenches by providing equivalent information quality, allowing utility surveyors to rely solely on GPR without compromising the required information for the project. However, this research demonstrated that the practical application of GPR exceeds this singular use.

In particular, GPR's use as a substituting tool proved to be its least successful application. The predominant roles observed were GPR's use as a supporting or complementary tool. This can be attributed to the uncertainties GPR faces in its application, as its performance is susceptible to (geo)physical conditions and the complexity of the utility infrastructure (Jol, 2009). Nevertheless, in scenarios where GPR could not replace trial trenches due to crowded utility areas causing overlapping hyperbolas, project teams still recognized its value in determining the optimal location for digging trial trenches. Since locations of trial trenches are based on utility maps, which are not always accurate and thus could lead to deviations from original plans, GPR proved helpful in pinpointing trial trench locations. Additionally, GPR was useful in locating undocumented utilities, allowing for a quick scan of the construction site to identify any type of anomalies. This avoided extensive, trial-and-error searches with trial trenches.

In complementary roles, GPR can survey locations adjacent to trial trenches to extend their findings. It can also be used where excavation is too costly or disruptive due to the material of the cover (e.g., asphalt) or the location (e.g., a busy road requiring a roadblock). In these situations, GPR provides additional insights into onsite utility locations that would otherwise be overlooked. In this complementary role, GPR allows for the acquisition of more information without compromising the need for highly accurate and comprehensive information obtained through trial trenches.

Communicating this versatility and broad applications of GPR to the utility sector can help guide future decision-making regarding its adoption and inform practical implementations on construction sites. Developing such an understanding among construction professionals may stimulate adoption rates (Lai et al., 2018), which, in turn, could lead to GPR's increased use and support for increasingly complex construction projects in urban areas (Metje et al., 2020).

8.2.2. *Hurdles to GPR-enhanced utility surveying*

The expert-based decision model developed in Chapter 6 aids construction practitioners in selecting the appropriate GPR deployment method for their surveying activities. It suggests one of three methods: using GPR as a standalone surveying method with post-processing radargrams, as a standalone method without post-processing radargrams, or as a complementary method alongside trial trench verification. This model supports onsite decision-making during utility surveying practices, facilitating better-informed decision-making regarding GPR deployment. When applied in construction site settings, the model can support utility surveyors, contractors, utility owners, and any organization involved in excavation, promoting a more effective and efficient surveying process. This is expected to help reduce utility strikes and improve productivity in the construction sector. Additionally, the model could complement the computer-aided utility strike risk analysis tool discussed in Chapter 7. Together, these tools guide users on where utility strikes are most likely to occur and how to survey effectively – determining whether GPR is suitable or if a trial trench is required.

However, implementing the decision model in surveying practices faces technical and systemic hurdles. From a technical perspective, the lack of a practical user interface for the decision model developed in Chapter 6 complicates its implementation on construction sites. While the decision model aims to address current knowledge deficiencies surrounding GPR, practical user interfaces are essential for making the decision model more productive and efficient (Holsapple, 2008; Power, 2008). Without such interfaces, construction professionals may perceive the model's use as complicated, disincentivizing its use in their surveying practices. Consequently, the absence of a practical user interface means that the decision model has only been evaluated in fictive cases in this PhD research, not real-life practice. Therefore, its practical impact on actual surveying practices remains untested. Similar to the study of GPR in this dissertation, contextualized studies of the model in practice are required to evaluate this impact.

Another technical hurdle emerges when GPR, the decision model, and risk analysis tools are widely used alongside trial trenching. Implementing these digital innovations will likely lead to a more comprehensive collection of utility information. While these insights are beneficial for reducing utility strikes, they are gathered in a highly fragmented sector. Implementing these innovations in practice could result in various ways of processing the accompanying data. As Timmermans and Epstein (2010) effectively described, we might face "a world of standards, but not a standard world." Without agreements on storing such data in digital models and establishing a uniform and consistent knowledge base, data interoperability may be compromised. As advocated in Chapter 7, this notion of digitization amid fragmentation could lead to digital hubris, posing challenges for aligning information systems between network operators and contractors. A shared domain understanding is vital for collaborative digital engineering practices. Ontologies have the potential to bridge fragmented digital realities. The ontology developed before this research and introduced in Chapter 7 could serve as the foundation for establishing a shared digital practice in the Dutch utility sector.

In addition to technical hurdles, the adoption of GPR also faces systemic barriers that explain why the technology has not yet become a common alternative to trial trenches in the Netherlands. Building upon the findings from Chapter 2, three self-reinforcing cycles were described in Chapter 7: the knowledge cycle, the institutionalization cycle, and the misalignment cycle. These cycles highlight that the limited adoption of GPR is driven more by a lack of legitimacy, knowledge, and institutionalized surveying procedures than by the technology's limitations.

- **Knowledge Cycle:** Limited understanding and awareness of GPR's capabilities and limitations hinder its adoption. Stakeholders are reluctant to invest in unfamiliar technologies without understanding their potential benefits;
- **Institutionalization Cycle:** Entrenched institutional practices favor traditional methods over GPR. This institutional inertia sustains the status quo and stifles innovation in surveying practices;
- **Misalignment Cycle:** Broader societal and institutional factors contribute to GPR's lack of legitimacy. Consequently, GPR struggles to gain traction as a viable alternative to trial trenches.

Increasing awareness and understanding of GPR among industry professionals and policymakers is recommended to facilitate the adoption of GPR and the decision model developed by this dissertation. This can be achieved by developing and evaluating educational and training programs focused on GPR usage, alongside implementing and assessing pilot projects that showcase its effectiveness in utility surveying. The local success stories of GPR applications highlighted in this dissertation underscore the importance of such initiatives. Additionally, creating a supportive regulatory environment for GPR adoption is crucial, starting with positioning GPR as a viable option within surveying directives. While the specifics of the three identified cycles may not universally apply to all contexts, the fundamental systemic challenges – including the lack of legitimacy, knowledge gaps, and entrenched surveying practices – likely represent common barriers beyond the Netherlands. These insights can serve as a foundational reference for other studies and inform broader strategies for policy interventions to accelerate the adoption of GPR.

Overall, the findings throughout this dissertation challenge the traditional emphasis on the technological excellence of GPR and advocate for establishing supportive institutional environments that can legitimize and facilitate the adoption of innovative solutions first. As workloads increase due to the ongoing energy, climate, and green transitions, and labor availability decreases, enabling the successful adoption of (digital) technologies that enhance productivity becomes more crucial than ever.

8.3. Reflection

Before outlining future research recommendations, I reflect on the methodological decision to draw inspiration from the engaged scholarship concept and on utilizing practice-based theories to elicit the socio-technical knowledge required to develop decision support and guidance for GPR-enhanced utility surveying.

Engaged scholarship, in line with Van de Ven’s framework (2007), shares common ground with Latour’s (1987) philosophy, emphasizing the connection between academic research and the real-world interplay of science, technology, and society. Latour and Van de Ven highlight the significance of comprehending technologies and their interactions with individuals. This socio-technical perspective emphasizes that science, technology, and society exist on a continuum of interrelationships. It is challenging to compartmentalize research on a specific technology like GPR from the socio-technical context shaping its use.

The engaged scholarship concept emerged as a robust methodological principle for gaining socio-technical insight into deploying GPR technology in construction site settings. By adopting the technology-in-practice perspective outlined by Orlikowski (2000), coupled with my role as an engaged researcher, I immersed myself in the actual construction site setting where GPR would be used. This engagement as an internal participant provided valuable socio-technical insights into the challenges, subtleties, and constraints encountered by construction practitioners during their ongoing surveying practices. The approach facilitated a deeper understanding of how GPR technology influenced and was influenced by utility surveying practices. It helped clarify the benefits and challenges associated with GPR-enhanced utility surveying, which was used to develop the operational decision support.

The methodological principles underlying the engaged scholarship concept and the technology-in-practice perspective aligned well with Peffers et al.’s (2014) actionable research steps within Hevner’s Design Science Research Methodology (DSRM) (2007). While adopting an engaged scholarship and technology-in-practice perspective facilitated the development of practice-based, socio-technical knowledge on the use of GPR, the DSRM cycle structured the technical development of decision support and guidance for GPR-enhanced utility surveying. Throughout the research process, I, as such, adhered to my pragmatism philosophy, aiming to find practical solutions directly contributing to the construction practice.

From this methodological perspective, the selected practice-based theories of routine dynamics, as per the framework outlined by Feldman et al. (2019), along with Engeström’s (2015) activity-theoretical perspective on activity systems, demonstrated their value through conceptualizations of the early-stage innovation adoption dynamics of GPR. The lens of routine dynamics facilitated the collection of insights into construction practitioners' thoughts and actions when encountering GPR technology in the field. It unraveled the early interactions between utility surveying routines and GPR technology, shedding light on change triggers that indicated the Dutch surveying routine's receptivity to adopting GPR.

Subsequently, activity theory and the method of formative interventions allowed for a deeper exploration of how this uptake might manifest in future surveying activities. While the lens of the routine dynamics focused specifically on the initial interactions, centering on individual thoughts and actions, the activity-theoretical lens helped bridge individual behaviors toward the formation of transformative activity system changes. Together, these theoretical lenses provided a comprehensive understanding of the local innovation adoption dynamics of GPR within construction site settings.

This dissertation's methodological approach and chosen theories offer valuable practice-based and socio-technical insights beyond the extensive body of GPR research conducted in controlled laboratory settings. While such settings are crucial for refining GPR radargram processing and interpretation techniques, they fail to capture how the technology influences and is influenced by utility surveying practices. Exploring and supporting GPR-enhanced utility surveying practices within a controlled setting would have limited our understanding of the intricate interplay between GPR technology and real-world surveying practices. In line with Van der Ven's perspective, compartmentalizing GPR from its socio-technical context could have resulted in decision support and guidance that do not fully align with the nuanced intricacies of practice. This could have compromised the practical effectiveness of the knowledge and solutions developed.

In sum, the combination of practice-based theories, methodological principles, and philosophical perspectives underpinning this dissertation articulates that socio-technical knowledge emerges when we acknowledge and embrace the intricate interactions between science, technology, and society. It emphasizes that engaged research is a constructive force in this regard, pivotal in shaping the future of these interconnected realms.

8.4. Recommendations for future research

This section outlines five recommendations for future research avenues. These recommendations center on further exploration and improvement of GPR-enhanced utility surveying practices. They align with my pragmatic philosophy of improving surveying and reducing utility strikes.

8.4.1. *Explore the sustainability of locally induced changes*

Chapters 3 and 4 delved into the local routine and activity changes from a micro-level perspective. At this level, I examined individuals' specific interactions, behaviors, and decisions as they integrated GPR technology into their daily activities within construction site settings. However, these studies did not encompass observing whether the local interventions involving GPR led to sustaining transformations in surveying routines and their underlying activities from a meso-level perspective. This prompts the question: Did the observed changes in practice persist over time? If not, what were the factors contributing to their discontinuation? Conducting follow-up inquiries with the organizations involved in the studied cases could yield valuable insights into the barriers or facilitators influencing the continued use – or lack thereof – of GPR.

Future research endeavors could also undertake longitudinal studies that track surveying practices over an extended period. These studies could explore how interventions with emerging technologies might induce sustained learning and transformation at the meso-level. In this context, the Cultural-Historical Activity Theory (CHAT) framework developed by Engeström (2015) again could prove valuable. Expanding the current culturally and historically aggravated utility surveying activity system to consider all interconnected operational, organizational, and institutional activities can elicit more profound insights into where and how change originates surrounding the introduction of GPR technology.

8.4.2. *Identify strategies to promote GPR adoption*

This dissertation, particularly Chapters 3 and 4, delves into the micro-dynamics of innovation adoption on construction sites. However, a broader exploration in Chapter 7, utilizing the Technological Innovation Systems (TIS) framework (Hekkert et al., 2007), reveals systemic barriers hindering the widespread adoption of GPR. This analytical framework allows us to view GPR as an emerging technology within the larger socio-institutional environment at a macro-level. The study identifies significant gaps in knowledge development among potential end-users, such as surveyors, contractors, and utility owners. Additionally, it highlights a lack of legitimacy for GPR, stemming from misconceptions about trial trenches being mandatory, insufficient emphasis on geophysical methods in legislation and directives, and previous unsuccessful GPR applications leading to reluctance toward future adoption. Moving forward, the focus shifts to strategies aimed at overcoming these barriers. What general strategies and policy interventions should be developed to accelerate GPR adoption in the Netherlands?

Constructive Technology Assessment (CTA) could serve as a valuable methodology for this research (Schot & Rip, 1997). CTA focuses on comprehensively understanding a technology's impact in terms of its legitimacy, acceptance, and adoption. By facilitating collaborative sense-making among diverse stakeholders, CTA ensures that all relevant concerns, needs, and perspectives are integrated into policy and strategy development. Combined with the insights from the TIS analysis, such a participatory approach provides a structured method for crafting effective strategies to overcome systemic barriers. The use of CTA, hence, could inform general strategies and policy interventions that expedite the integration of GPR into utility surveying and other relevant domains.

8.4.3. Assess practical user interfaces and visualization techniques

While the developed decision model of Chapter 6 may help address current deficiencies in knowledge and potentially enhance the legitimacy of the GPR, integrating the model into Decision Support Systems (DSS) can significantly enhance its effective use on construction sites. These practical user interfaces streamline decision-making processes, making them more productive and efficient (Holsapple, 2008; Power, 2008). The question remains: What practical user interface best fits the problem, and how should the decision model's outcomes be visualized for maximum effectiveness?

Given the nature of the decision problem related to GPR, Spatial Decision Support Systems (SDSS) appear to be a promising approach. SDSSs are equipped with powerful geographic tools to assist decision-makers in addressing spatially related challenges. They achieve this by integrating spatial and non-spatial data, performing spatial analyses, visualizing spatial maps, and predicting decision outcomes (Keenan & Jankowski, 2019). Future research should explore incorporating the decision model developed in this dissertation into such SDSSs. Once integrated, the decision model's practical application can be more easily studied. This would empower practitioners to take control of the system, enabling an evaluation of the tool's effectiveness in real-world settings.

8.4.4. Diversify the 'surveying toolbox'

This dissertation primarily focused on using an air-coupled impulse GPR equipped with a 500 MHz antenna, advocating for its use alongside trial trenches. However, numerous other geophysical surveying methods exist, including alternative GPR types and antenna specifications, the Cable Avoidance Tool (CAT), acoustic technologies, and electromagnetic locating (EML) (Metje et al., 2007). Controlled laboratory environments could serve as a starting point to explore the technical capabilities of these methods. The ongoing development of the Living Innovation Lab (LILa) field lab at the University of Twente presents an opportunity to facilitate such research. Additionally, researchers could adopt an engaged technology-in-practice approach, like the one employed in this dissertation, to capture the context-specific values of these methods within surveying practices. The question then arises: How can these methods synergize effectively?

Expanding the surveying toolbox requires specific guidance for surveying professionals on the optimal locations for each method and, perhaps, even the order of application. A logical first step is to provide construction workers with insights into where to dig a trial trench, aligning with areas where the decision model recommends a complementary and supporting role for GPR. In this context, the work of Racz (2017) becomes relevant, offering a risk-driven decision support system that determines trenching locations based on the potential consequences of utility strikes. Integrating the insights from Racz's system with the decision models developed in this dissertation can further empower construction professionals to make informed decisions about the combined use of GPR and trial trenches on construction sites. Subsequent integration of other surveying methods can follow a similar approach.

8.4.5. *Outline pathways to a shared digital transformation*

Collecting utility information through methods like GPR is one; the next crucial step is processing this information into digital models. The necessity for such digital models, capable of capturing surveying data, becomes increasingly evident as we strive for more accurate and comprehensive information about underground infrastructure. Sharing this information is vital in our efforts to reduce utility strikes. However, achieving this poses challenges due to the fragmented nature of the utility sector, which complicates the harmonization of diverse organizational information models. Chapter 7 introduced prior work on an ontology designed to address this challenge. However, integrating such models requires systemic change, possibly necessitating policy intervention. Many organizations are in a 'lock-in' situation, bound by proprietary systems or custom software. Given the substantial costs of transitioning to new digital systems, organizations often hesitate to undertake such transformations independently. Future research could delve into systemic challenges and explore policy interventions needed to navigate this path toward a shared digital future.

Chapter 9

conclusions

9. Conclusions

Inaccurate and incomplete utility maps, along with intrusive, disruptive, and location-specific trial trenches, have prompted the exploration of the geophysical GPR method as a non-intrusive and rapid alternative. However, its local use dynamic within construction site settings remains inadequately understood. There is a lack of insight into how GPR influences and is influenced by practical construction site situations. Consequently, construction practitioners have an insufficient understanding of when, where, and how to deploy GPR. This has led to failed applications and limited adoption of the technology.

This dissertation filled that gap by providing context-rich, practice-based insights into how GPR impacts and contributes to surveying practices. These insights deepen our socio-technical understanding of the benefits and challenges associated with GPR-enhanced utility surveying and were used to develop operational decision support for construction workers deploying GPR onsite. To this end, this dissertation addressed the following research objective:

To explore and support ground penetrating radar-enhanced utility surveying practices.

To achieve the objective, Chapter 6 highlighted the effectiveness of expert-based decision models for providing onsite decision support in GPR-enhanced utility surveying. This chapter, along with outlining GPR deployment strategies in Chapter 5, describing an interventionist approach and the identification of three future roles for GPR in Chapter 4, identifying change triggers within surveying routines in Chapter 3, and explaining the constrained structure of Dutch surveying practices in Chapter 2, collectively provided practical and scientific knowledge clarifying the deployment of GPR in utility surveying. These five research chapters culminated in a decision-making model designed to support onsite decisions in utility surveying practices. The following sections outline the main conclusions of each chapter and conclude with an outlook on GPR-enhanced utility surveying.

9.1. Conclusions per chapter

This section summarizes the conclusions of each research chapter in this dissertation and elaborates on their contributions to the research objective of exploring and supporting GPR-enhanced utility surveying practices.

9.1.1. A constraining structure

In Chapter 2, I explored the structure of the Dutch utility surveying practice and the specific role of GPR within it. I delved into the various surveying methods employed for utility localization before excavation. This chapter draws on qualitative insights from Dutch legislation, directives, and practical utility surveying work plans. My analysis revealed that the Dutch surveying practice primarily uses statutory record verification through trial trenching. Geophysical methods, including GPR, receive comparatively little emphasis within the framework of legislation and directives. The deployment of GPR was also absent in the surveyed practices and their corresponding work plans.

A reasonably complete and regulated central utility data exchange platform, KLIC, contributes to this surveying practice structure. Additionally, the legal requirement for precise utility location before excavation is often interpreted as necessitating trial trenches, creating a contested environment for GPR technology adoption. Above-ground surveying methods like GPR inherently introduce higher levels of uncertainty when contrasted with the tried-and-tested method of trial trenching. Furthermore, the assurance of access to comprehensive utility records seems to have led to a reduced perceived need among surveyors to integrate geophysical methods into their surveying practices.

In conclusion, the chapter revealed that the Dutch utility surveying practice presents a seemingly constrained structure that marginalizes the role of GPR. This contributes to the research objective by providing a contextual outlook on the technology-in-practice structure of GPR. It emphasizes that Dutch legislation, directives, and work plans form a structure that must be considered when studying its local use dynamics, as this structure mediates how those dynamics unfold. Therefore, this exploratory study provided the necessary context for analyzing the interaction structure enacted when professionals engage with GPR in the subsequent chapters.

9.1.2. A local receptiveness to GPR uptake

In Chapter 3, I applied the theoretical lens of routine dynamics, as proposed by Feldman et al. (2019), to unravel the early interactions between utility surveying routines and GPR technology. This investigation encompasses five construction projects involving organizations without prior GPR usage experience. Through interviews, onsite observations of surveying activities, and intervention research, I found that introducing GPR triggers routine change and stability mechanisms.

In situations where established routines proved ineffective, particularly when disruptions and shortcomings became apparent, workers were prompted to reflect on their routines and consider the potential of GPR technology as an alternative solution. As they delved into this exploration and began to use GPR, it gave rise to fresh user experiences. These experiences reshaped their expectations and powered the continued utilization of GPR in subsequent surveying activities. This marked the initial stages of what could potentially become a routine change. Conversely, when routines functioned as expected and proved effective, they shielded workers from the uptake of GPR. This safeguard mechanism contributed to routine stability.

The chapter conceptualized these findings through an empirical model that illuminates the mechanisms governing routine change and stabilization during the early stages of introducing emerging technologies into construction site settings. The lens of routine dynamics provided a valuable framework for acquiring socio-technical insights into the susceptibility of existing surveying routines to change and their receptiveness to the uptake of GPR.

In conclusion, this chapter demonstrated the local receptiveness of the Dutch utility surveying routine to GPR uptake. Its practice-based approach provided valuable insights into GPR's technology-in-practice enactment. It contributes to the research objective by explaining the early interactions between utility surveying routines and GPR technology. It sheds light on change triggers that allowed for the uptake of GPR and provides a first understanding of its local use dynamics. Building on these results, the next logical step was to investigate how this uptake might transform future surveying activities.

9.1.3. Three roles for GPR in utility surveying

In Chapter 4, I explored a renewed participatory approach to the role of the interventionist researcher, using the Cultural-Historical Activity Theory's method of formative interventions to identify potential future impacts of GPR. The chapter delves into how interventions with emerging technologies like GPR can reshape ongoing activities, potentially leading to new and advantageous 'futures.' By 'futures,' I mean transformations in activity systems that could pave the way for new and unforeseen uses of GPR. As an interventionist researcher, I actively participated in utility detection activities across thirteen construction sites during this study, introducing and facilitating GPR as an alternative to established surveying methods.

The chapter revealed five interventionist action types for studies with emerging technology: shaping conditions, exposing tensions, supporting problem resolution, operating tools, and facilitating reflection. These actions prompted subjects to reevaluate elements of the activity system and helped describe three potential future activity systems integrating GPR as a new tool. These transformations position GPR not only as a substitution for trial trenches in utility verification, which is conventionally associated with GPR, but also as a complementary and supporting tool for existing methods. Notably, the latter two roles were most prevalent in the study.

Beyond enriching the interventionist epistemology of activity theory as presented in Engeström et al. (2014), Sannino (2011), and Sannino et al. (2016) with a renewed participatory take on formative interventions, the study's findings demonstrated that such an approach offers a powerful means to uncover future, rather than given, activity systems incorporating emerging technologies. The five formal intervention action types offer future researchers in interventionist studies valuable methodological tools to apply CHAT in practice-based explorations of emerging technologies. These tools facilitate the study of the flexibility in how technology-in-practice unfolds, emphasizing its contextual nature and practices' specific and local implications. While this study focused on unraveling the potential future impacts of GPR, numerous emerging technologies are poised to enter construction practices, the future impacts of which remain uncertain but could be studied through a similar approach.

In conclusion, this chapter identified three potential future roles of GPR that emerged from transformations within activity systems. These roles contribute to the research objective by offering practical insights into the benefits and challenges of GPR use in utility surveying. This practice-based study deepened the understanding of the interactions between individuals and GPR technology. These insights into local use dynamics informed the development of specific GPR deployment strategies for each utility activity studied. The next chapter formally outlined these strategies in a comprehensive dataset.

9.1.4. GPR deployment strategies outlined as data

In Chapter 5, I utilized the socio-technical insights gathered from the practice-based studies of the previous chapters to outline local GPR deployment strategies into a dataset. From these strategies, three primary GPR deployment methods emerged: using it as a standalone surveying method with post-processing radargrams, as a standalone method without post-processing radargrams, or as a complementary method alongside trial trench verification. The dataset encompassed 125 utility surveying activities conducted across thirteen construction projects in the Netherlands. It provided comprehensive details for each GPR deployment strategy, including the chosen method, collected radargrams and trial trench data, and metadata about the construction context, geophysical setting, infrastructure present, and technical specifications of the GPR equipment used.

While this chapter may not yield definitive conclusions, it addressed the challenge of the scarcity of data on GPR deployment within practical construction site settings. Unlike controlled or laboratory-based settings, this dataset originated from construction site settings, offering valuable empirical insights into the actual deployment of GPR in surveying practices.

In conclusion, the practice-based studies leveraged 125 GPR deployment strategies that were outlined in a dataset in this technical study. The dataset was pivotal in achieving the research objective. It served as the foundation for developing machine learning-driven decision models. The next chapter involved developing and assessing a range of these.

9.1.5. An expert-based decision model for GPR-enhanced utility surveying

In Chapter 6, I assessed the effectiveness of both expert-based and generalized machine learning-driven decision models in aiding construction practitioners in selecting GPR deployment methods for utility surveying activities. These models include the expert-based Case-Based Reasoning (CBR) and the generalized models of Decision Trees (DT), Random Forest (RF), and Support Vector Machine (SVM). The training of these models was based on the dataset developed in Chapter 5. A stratified 5-fold cross-validation approach was used during this training process. Validation was conducted using 31 unseen expert decisions. The results demonstrated that CBR outperformed the other generalized models, correctly predicting 27 instances and achieving an overall accuracy and F1-score of 0.87.

The findings revealed that the expert-based decision model of CBR most effectively supports onsite decision-making involving GPR. Such experience-driven operational decision-making problems are common in construction and may inform the development of other operational decision models in the sector. Additionally, the findings demonstrated that expert-based models like CBR can outperform generalized models such as DT, RF, and SVM when dealing with limited empirical training data. These findings may extend beyond GPR method selection to other construction contexts where data scarcity challenges the decision problem to be supported.

In conclusion, this chapter revealed that the expert-based Case-Based Reasoning (CBR) decision model emerged as the most effective method for selecting the GPR deployment method in surveying activities. This model contributes to the research objective by providing practical support to construction workers in effectively deploying GPR-enhanced surveying practices.

9.2. Final remarks and outlook

Underground infrastructure is crucial for society, providing essential services like water, electricity, and telecommunications. However, excavation work often damages this critical infrastructure in the Netherlands and beyond, making utility strikes a pressing concern that should remain at the forefront of industry agendas. This concern may become even more significant due to ongoing societal developments such as the energy transition, climate adaptation, and modernization of telecommunications networks. With the number of reported excavation activities rising from 624 thousand in 2018 to 798 thousand in 2022 in the Netherlands, utility strikes have seen a similar increase (RDI, 2023). Meanwhile, the construction sector faces a growing shortage of personnel, with limited people entering the industry. Additionally, the aging workforce in the Netherlands exacerbates this situation, resulting in more work with fewer people. Consequently, work pressure is likely to increase while decreasing utility strikes remains critical.

To combat utility strikes, it is crucial to examine one of their primary drivers: the drawbacks of conventional surveying methods to locate utilities before excavation. Trial trenches only offer local insights and are typically dug in limited numbers due to their labor-intensive and costly nature. Furthermore, utility maps tend to be inaccurate and incomplete. The question arises: How can we comprehensively understand underground utility locations while still relying predominantly on these methods? The geophysical ground penetrating radar (GPR) method has the potential to mitigate the drawbacks of trial trenches and utility maps while also increasing productivity. However, although GPR technology has been around for decades, its adoption in the Dutch utility sector remains limited.

While much research has focused on improving the technical aspects of GPR technology, particularly data processing and interpretation, there is an insufficient understanding of its local use dynamics within practical construction site settings. Do stakeholders possess the required knowledge to employ GPR effectively? What specific information are they seeking from GPR? How does GPR integrate into current work practices, and what roles can it fulfill? In this dissertation, I addressed these questions by leveraging a pragmatism research philosophy to translate socio-technical insights derived from the practical exploration of GPR into decision support and guidance for construction workers. The dissertation provided practical tools and knowledge that I believe can directly facilitate the use of GPR on construction sites and contribute to reducing utility strikes.

Despite this promising outlook, I feel compelled to highlight some practical implications in this concluding section of my dissertation. Throughout my PhD journey, I found the Dutch utility sector lacking in knowledge development and legitimacy for GPR, hampering the technology's widespread adoption. In particular, practitioners often had misconceptions about GPR, perceiving it as a direct replacement for trial trenching. However, I must emphasize that GPR is not a 'magical box' but rather a tool with technical limitations. This dissertation provided empirical evidence that GPR functions best as a tool used alongside trial trenches rather than as a standalone solution. It may complement trial trenches by scanning areas unsuitable for trenching. It can also act as a supporting technology to pinpoint the optimal location for trenching. Therefore, conveying a realistic understanding of GPR's capabilities and limitations to construction practitioners is crucial. I believe research institutes and industry associations should increasingly play a role in facilitating learning about the different roles of GPR in utility surveying practices, as identified in this dissertation.

In conclusion, this dissertation contributed to both the construction research domain and the utility sector by offering conceptualizations of early-stage innovation adoption dynamics, a bespoke methodological approach to study emerging technologies, evidence for using expert-based decision models to capture intricate context-based decision problems, and practical tools and knowledge for navigating underground utilities with GPR. These contributions have the potential to expedite the adoption of GPR, thereby improving the effectiveness, efficiency, and safety of utility surveying practices. Realizing this potential in the Dutch utility sector necessitates communicating a realistic understanding of GPR's value within the surveying context, implementing systemic changes to enhance its legitimacy, and educating practitioners and organizations on its use. In an era where productivity is a pressing concern and the number of utility strikes is expected to rise, the insights presented in this dissertation serve as a valuable resource in this regard.

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List of publications and under-review materials

Papers included in this dissertation as chapters:

Chapter 2:

Ter Huurne, R.B.A., Olde Scholtenhuis, L.L., and Dorée, A.G. (2020). Mutual Learning: A Comparison between the Dutch and International Utility Surveying Practices. In: J.F. Pulido and M. Poppe (Eds.), *Pipelines 2020: Utility Engineering, Surveying, and Multidisciplinary Topics*. ASCE, San Antonio, Texas, USA, 372-380.

Chapter 3:

Ter Huurne, R.B.A., Olde Scholtenhuis, L.L., and Dorée, A.G. (2022). Change Triggers in Early Innovation Stages: How Technology Pilots Enable Routine Reflection. *Journal of Construction Engineering and Management*, *148*(9), 1-10.

Chapter 4:

Ter Huurne, R.B.A., Olde Scholtenhuis, L.L., Dorée, A.G., and Van Oers, B. (2024) Using formative interventions to study emerging technologies in construction practices: The case of the Ground Penetrating Radar. *Journal of Construction Management and Economics,* 1-20.

Chapter 5:

Ter Huurne, R.B.A., Olde Scholtenhuis, L.L., and Dorée, A.G. (2024). Ground Penetrating Radar at Work: A Realistic Perspective on Utility Surveying in the Netherlands through a Comprehensive Ground-Truth Dataset. *Journal of Data in Brief*, *54*, 1-11.

Chapter 6:

Ter Huurne, R.B.A., Olde Scholtenhuis, L.L., and Dorée, A.G. (under review) Assessing decision models that support Ground Penetrating Radar enhanced utility surveying.

Related works

International scientific conference papers:

Ter Huurne, R.B.A., Olde Scholtenhuis, L.L., and Dorée, A.G. (2018). Digitization for Integration: Fragmented realities in the utility sector. In: Gorse, C., and Neilson, C.J. (Eds.), *Proceedings 34th Annual ARCOM Conference: Working Papers*, Belfast, UK, 92-100.

Ter Huurne, R.B.A. (2021). The Role of Risk Attitudes: Discrepancies Between Human and Computer-Based Risk Analysis in the Utility Sector. In: Scott, L, and Neilson, C.J. (Eds.), *Proceedings 37th Annual ARCOM Conference*, UK, 844-853.

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Epilogue

This journey began with the following question: how to explore and support ground penetrating radar (GPR) enhanced utility surveying? After many years of research, and reflection, this journey concludes with a decision model that supports effective decision-making regarding when, where, and how to deploy GPR. As I write this epilogue, I cannot help but look back on the trials and triumphs of my PhD journey and the path that has led me here.

During this research…

My research objective was clear: to improve GPR surveying practices by developing decision support and guidance that empower workers to make well-informed choices about deploying this technology, all with the intent of reducing the number of utility strikes. Although it was initially difficult to translate this pragmatic objective into an academic pursuit, the objective served as my compass, navigating me through the intricate realm of underground infrastructure, technology adoption dynamics, and GPR's surveying capabilities. I spent many hours on construction sites, engaging with professionals to gain a deep understanding of their practical needs.

Throughout this journey, I admired how GPR, initially met with skepticism, evolved into a valuable tool for construction organizations. It was fascinating to observe the acceptance and integration of GPR into practice step by step. It illustrated the remarkable synergy that occurs when science, technology, and society converge, resulting in the novel insights presented in this dissertation. It confirmed my passion for engaged research in practice, where I, as a researcher, can actively contribute to meaningful change.

Lessons and Growth…

My journey as a PhD candidate shaped me as a researcher and individual. Pursuing a PhD is no easy feat, and my journey was further complicated by the turbulent times I had to navigate. These included dealing with the disruptions brought by the COVID-19 pandemic, overseeing and contributing to the construction of my home, and confronting personal hardships. Looking back, this period stands as a testament to unwavering hard work – days that would commence in the office and often conclude at the construction site of my home, week after week.

Through these challenging times, I learned that perseverance and determination are vital to overcoming the many hurdles encountered during a PhD journey. I discovered that research is not a linear path but a series of ups and downs and that failures can be just as valuable as successes. It made me see each setback as an opportunity to learn and grow. These experiences have deepened my appreciation for research as a multifaceted journey that lacks a one-size-fits-all recipe for success.

With Gratitude…

Looking at the present, I am filled with happiness and pride, for persevering through has resulted in completing this dissertation. However, my journey would never have been possible without the support of many. First and foremost, I extend my sincere appreciation to various organizations, with a special mention of GasUnie, Alliander, and MapXact, for their resources that made this research endeavor possible. I am also grateful to the organizations that allowed me to introduce GPR into their utility surveying practices. To the dedicated professionals in the field, I extend my thanks for the invaluable insights you shared during our time together.

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Finally, I must extend my heartfelt thanks to my friends and family. I may not have discussed my work in great detail with all of you, but you provided the much-needed respite that allowed me to relax, clear my head, and gather fresh energy to continue my journey toward completing my PhD. A special shout-out to my long-time friends Jordy, Priyan, Tim, and Tom. Additionally, I am deeply grateful for the unconditional love and support of my family – my parents, Jan and Jolanda, and my sisters Kirsten and Milou. However, a special last mention must be reserved for my life companion, Evelien. You have been my unwavering support throughout this entire journey. You steadfastly stood by me, no matter how hectic life became. I can imagine that living with a PhD candidate presented its challenges, yet you not only persevered but did so with grace, and for that, I love you all the more.

Reflection…

A PhD journey goes beyond the acquisition of knowledge; it is a philosophical journey. It challenges us to think deeper about the nature of knowledge, truth, and innovation. It is a journey that compels us to question, to doubt, and to explore. It teaches us that beauty lies in the unknown and that progress begins with asking the right questions.

As I write this epilogue, I look back with pride on my journey as a PhD candidate and look forward to the next phase of my academic career. I sincerely hope that the insights and solutions within my dissertation contribute to a better future for the utility surveying practice, ultimately leading to a safer and more efficient society.

With warm regards,

Ramon ter Huurne

About the author

Ramon ter Huurne was born in 1993 in Buurse, the Netherlands. He obtained his Bachelor's degree in Civil Engineering in 2014 and his Master's Degree in Construction Management and Engineering with honors in 2017. Ramon completed an Engineering Doctorate (EngD) program with honors in 2019, during which he developed an ontology to support the operations and maintenance of underground utilities. This initial foray into the realm of underground utilities paved the way for Ramon's transition into the PhD trajectory that forms the foundation of this dissertation.

As an EngD and PhD researcher, Ramon acquired expertise across various domains, including the utility sector and its surveying practices, ground penetrating radar (GPR), 3D asset modeling, ontology development, and machine learning-driven decision solutions. He organized workshops to discuss the value of 3D modeling and GPR in construction and presented his research at national and international conferences. Additionally, Ramon tutored during BSc and MSc graduations and co-instructed on several courses, including 'Smart Ways to get Smart Cities Smarter,' '3D Modeling for City Digital Twins,' 'BIM and 5D Planning,' 'Digital Technologies in Construction,' and 'Subsurface Infrastructure Engineering.'

Ramon has continued his academic career as an Assistant Professor at the University of Twente. In this role, he focuses on digitization, digitalization, and digital transformation within the construction context. He coordinates and develops the MSc course 'Digital Technologies in Construction' and participates in the LILa (Living Innovation Lab), ReDUCE (Reduction of Damage to Utilities and Careful Excavation) and Lifelong Learning Catalyst programs, contributing to ongoing research and innovation in the field.

Utility strikes result in cost overruns, service disruptions, environmental damage, and safety risks. Ground penetrating radar (GPR) offers a non-intrusive, rapid surveying method to mitigate these issues. However, its effectiveness is often hindered by insufficient insights into its local use dynamics, leading to failed applications and limited adoption. This PhD dissertation addresses this gap by offering context-rich, practice-based insights into GPR's use in utility surveying. Through a bespoke methodological approach, it identifies three key roles for GPR and develops a machine learning-driven decision support model to help construction practitioners apply GPR effectively. By providing practical tools and knowledge for navigating underground utilities with GPR, this dissertation aims to enhance its local use and contribute to reducing utility strikes.