

EXPLORING THE BARRIERS OF GROUND PENETRATING RADAR ADOPTION: A TECHNOLOGICAL INNOVATION SYSTEM ANALYSIS

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Rapid urbanisation, digitalisation, and ongoing energy transitions have increased excavation activities, thereby increasing the risks and consequences of utility strikes. Ground Penetrating Radar (GPR) is a promising innovation to enhance utility surveying, offering advantages over traditional methods like trial trenching. Despite its potential, widespread GPR adoption remains limited. This study applies the Technological Innovation System (TIS) framework to uncover systemic barriers hindering GPR adoption within the broader socio-technical context of the Dutch utility sector. Data were gathered through semi-structured interviews, industry meetings, questionnaires, field observations, and a review of grey literature. Qualitative coding of this data revealed three systemic lock-in cycles. These cycles highlight that the limited adoption of GPR is primarily driven by institutionalised surveying practices that exclude GPR, a lack of legitimacy, and insufficient knowledge development and diffusion. By reframing the challenge of GPR adoption as one of social and institutional alignment, this study offers initial insights into systemic barriers in the Netherlands. It provides a foundation for developing comprehensive strategies to overcome these barriers and facilitate broader adoption of GPR within the utility sector.

Keywords: barriers; ground penetrating radar; technology adoption; Technological Innovation System; utility infrastructure

INTRODUCTION

Urbanisation, digitisation, and the energy transition contribute to a growing underground cables and pipes. A failure to acquire accurate information on these utilities' whereabouts often leads contractors to strike utilities during excavation tasks. Such strikes lead to delayed construction works, expensive repairs, societal nuisance, utility outages, and safety issues (RDI 2023; PHMSA 2024). Trial trenches are the current predominantly applied utility surveying method for acquiring this information about utilities. This method involves exposing utilities through excavation, providing a highly accurate insight into the location of the utilities at the excavated area. While digging trenches successfully detects utilities, it provides only local insights, is labour-intensive and expensive, and may cause utility strikes itself.

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Trenchless methods have been introduced as alternatives to trial trenches, including acoustic technologies, quasi-static fields, and ground penetrating radar (GPR) (Costello *et al.*, 2007; Metje *et al.*, 2007). From these alternatives, scholars suggest century-old ground GPR technology as a highly promising surveying method. GPR is capable of detecting utilities of all types, regardless of their discipline, material, or diameter (Utsi 2017). While facing challenges such as signal issues in clay soils and potential clutter in dense utility areas (Costello *et al.*, 2007; Metje *et al.*, 2007), GPR offers a rapid, cost-effective, and non-destructive method for utility detection (Lai *et al.*, 2018).

Despite the merit GPR can bring to practice, the technology's use on construction sites is low (Lai *et al.*, 2018). While there are plenty of studies aiming at enhancing GPR's utility detection capabilities from a technological perspective (Ghanbari *et al.*, 2022; Siu and Lai 2019), an explanation of why the adoption of this technology into the utility sector's practices does neither significantly scales up nor completely phases out is lacking. To obtain such understanding, the broad socio-technical system must be understood. After all, the replacement of trial trenches by GPR requires not only technological adoption but also considerable changes in behaviour and institutions (Ter Huurne *et al.*, 2022). Unfortunately, studies that explore the adoption of GPR from such a systemic, socio-technical perspective are missing.

To address this, this study explores why GPR has not become a common alternative to trial trenches by uncovering the systemic barriers through a socio-technical systems perspective. This perspective considers both technological factors and the social and institutional dynamics surrounding GPR's introduction. For its ability to consider the interactions between technology and its social and institutional settings (Markard and Truffer 2008), we employ the Technological Innovation System (TIS) as an analytical framework (Bergek 2019). By identifying the systemic barriers that hamper the breaching of the locked-in trial-trench practices and adoption of GPR, we aim to provide insights for scholars and policymakers on the unusual adoption dynamics of GPR. These insights can either guide efforts to support GPR adoption or suggest pursuing other alternatives. Our case study focuses on the Netherlands, where GPR adoption has been notably limited and its potential utility and constraints remain under-discussed (Ter Huurne *et al.*, 2020).

The remainder of this paper follows: First, we introduce the TIS framework and explain how we used its seven functions to map the GPR's adoption context. Then, we elaborate on our research methods before we present our findings. Finally, we reflect on the implications of our findings and conclude our article.

Analytical Framework

Innovation Systems describe the whole of components, relationships, and attributes in the development and diffusion of innovation (Carlsson *et al.*, 2002). Considering the system boundaries around the product (i.e., GPR) and its applications (i.e., detection of underground utilities), we employ the TIS approach as the central analytical framework. TISs are used to analyse the introduction of a focal technology or product. Notably, their ability to provide a view of the dynamics through the structural-functional approach make TISs applicable to reveal fundamental barriers that not only relate to structural elements but also the socio-technical system's functional dynamics (Hekkert *et al.*, 2007; Markard and Truffer 2008). As we are particularly interested in adopting GPR for detecting underground cables and pipes, we confine our TIS to the boundaries of the Sectoral Innovation System (SIS) related

to the underground infrastructure sector. A TIS analysis generally consists of three steps.

First, a structural approach defines the SIS in terms of actors, networks and institutions that affect or are potentially affected by the technology's introduction (Bergek 2019). This includes the types and number of actors as well as their relations and general behaviours. Moreover, the institutions comprising the system's formal and informal norms and rules are studied to explain the system structure. This part explains the current state of the socio-technical system under study.

Second, a functional approach is taken to explain the system's dynamic performance. The functional approach considers events that enable or hamper the introduction and diffusion of the technology. This step aims at surfacing insights into the dynamics that present barriers and opportunities with respect to advancing the focal technology (Hekkert and Negro 2009). The analysis is based on seven empirics-derived system functions that have been theoretically derived and empirically verified through a plethora of studies since the early 2000s (Bergek 2019). Due to its general acceptance in TIS literature, we adopt a list of seven functions (SF) as defined by Hekkert and Negro (2009; Table 1). Essentially, each system function can be understood as an abstract category of (collectives of) activities that affect technology development. For example, when subsidies are introduced to use a technology, this can be considered an act of resource mobilisation (SF6). The assumption is that a sufficient presence and a smooth interaction between all functions results in an innovation system where the technology can successfully develop and diffuse.

Table 1: Seven TIS functions and their explanation (based on Hekkert and Negro 2009)

#	System Functions	Function description
SF1	Entrepreneurial Activities	Identifying and seizing business opportunities by leveraging new knowledge, networks, and market potential.
SF2	Knowledge Development	Conducting research and development, actively seeking new knowledge, and learning through practical experience.
SF3	Knowledge Diffusion	Networking, information exchange, and collaborative and interactive learning to exchange both tacit and codified knowledge across the system.
SF4	Guidance of the Search	Clarifying user needs, setting policy goals, and shaping expectations to guide technological innovation efforts towards specific objectives.
SF5	Market Formation	Creating protective niche markets and policies for new technologies, providing the incentives to encourage their adoption.
SF6	Resource Mobilisation	Allocating financial, human and other types of resources to fulfil other system functions.
SF7	Creation of Legitimacy	Advocacy, coalition-building, and lobbying efforts to establish legitimacy for new technologies and overcome resistance from entrenched interests.

The third and final step is to determine the causality between the various activities, related to the functions. By studying causality between the functional and structural elements through the analysis of the underlying activities, underlying reasons and lock-ins can be found that affect the uptake of the innovation. This final step results in the identification of systemic, self-reinforcing cycles of barriers that provide insights to intervene in the current system beyond the focus on mere symptoms.

METHOD

In our exploration of the systemic barriers hindering the adoption of GPR in the Dutch utility sector, we applied the analytical framework presented in the previous section.

Using this framework, we aimed to identify system lock-ins, providing insights for policymakers to act. Before delving into our data collection and analysis methods, we briefly introduce the case of our study: the Dutch utility sector.

The Netherlands boasts an extensive network of underground utilities spanning 1.7 million kilometres. In 2022, nearly 800,000 excavation activities and 47,000 utility strikes occurred, resulting in 38.4 million euros in direct repair costs (RDI 2023). Telecommunication and low-voltage electricity cables were most affected, with activities such as reconstruction and utility line installations contributing to over half of all strikes. National regulations govern the excavation activities, mandating thorough research into utility locations. To comply, utility owners and contractors primarily rely on digital utility maps and trial trenches (Ter Huurne *et al.*, 2020). These maps are accessible through a national data exchange platform, aiding organisations in pinpointing utility locations during surveying, often validated through trial trenching.

Case data were collected through a comprehensive approach. We conducted semi-structured interviews with 12 contractors, including project managers and foremen, focusing on surveying procedures, localisation approaches, and perspectives on GPR. Each interview lasted approximately one hour. We attended 4 industry meetings where utility localisation was a primary theme. These meetings involved various stakeholders such as contractors, grid operators, utility owners, national authorities, research institutes, and technology developers. Discussions and observations during these meetings were noted, covering topics like localisation procedures, utility information documentation, and technological innovations including GPR. A questionnaire combining open and closed questions was distributed to 8 GPR experts to explore the technical and practical implications of using GPR for utility localisation. We reviewed grey literature containing regulations, rules, and directives on utility localisation in the Netherlands. Relevant passages concerning surveying approaches and GPR were abstracted for analysis.

Data were analyzed through a two-stage process. First, we mapped the structural components of the surveying chain, including actors, institutions, networks, and technology. Insights from the attended industry meetings and the grey literature were primarily used to develop this. Subsequently, we conducted the functional analysis utilising the analytic coding procedures outlined by Corbin and Strauss (2008). This process involved open coding in the Atlas.TI tool to systematically assess all data line-by-line. We coded the transcripts of the interviews, notes of the observations, notes from the industry meetings, the filled-out questionnaires, and the highlighted passages from the grey literature. Following the open coding phase, we categorised these codes through axial coding. This categorisation utilised the framework of seven system functions, detailed in Table 1, wherein codes were assigned to relevant functions. This approach ensured each code contributed to understanding one or more system functions. Through this analysis, we identified various systemic barriers and four significant system lock-ins, as elaborated on in the next section.

FINDINGS AND DISCUSSION

This section uncovers the systemic lock-ins hindering GPR adoption within the broader socio-technical context of the Dutch utility sector. Before we explain these, we first outline the structural and functional analyses.

Structural analysis

The Dutch utility sector comprises various types of actors, networks, and institutions (Figure 1). Actor types include the demand side, supply side, research programmes, institutes and universities, national industry associations, and authorities. The demand side comprises entities directly involved in surveying activities, including those requesting surveying, such as municipalities, semi-public and private utility owners and grid operators, and those conducting the surveying, such as excavation and surveying contractors. Conversely, the supply side consists of actors engaged in developing surveying equipment and methods, advancing solutions like GPR for use by clients. This group includes investors, GPR developers, land surveying companies, and GPR service providers. Research programmes, institutes, and universities also contribute to this development. Local and national authorities govern the Dutch utility sector through national rules and regulations. Together, these actor types form networks within national industry associations, which develop knowledge and establish guidelines and directives for careful excavation processes.

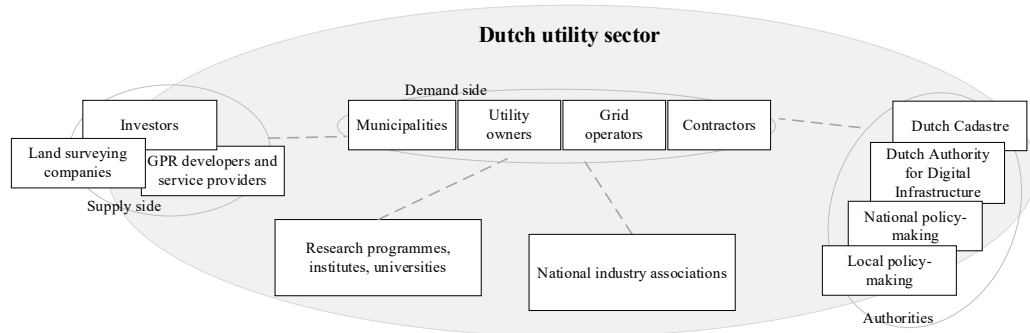


Figure 1: Main actors of the Dutch utility sector

All actors involved in works with or near underground utilities must comply with national legislation to safeguard the public domain. This includes a duty to carefully excavate, necessitating exact determination of underground utility locations before construction begins. This process is facilitated by a national 'careful excavation' directive, recognised by Dutch courts as the compliance standard. Actors are supported in underground works through a national data exchange platform providing utility maps. Requesting and using these maps is mandatory for excavation works, requiring utility owners to update utility maps on the platform when necessary.

Furthermore, the sector is characterised by a tight labour market and increasing spatial pressure on the underground. Work pressure rises due to energy, climate, and green transitions, necessitating more underground work. However, labour availability decreases, resulting in more work with fewer people under increasing time and financial constraints. Additionally, the sector maintains a relatively conservative culture, with long-standing work methods and risk aversion. The use of common surveying methods have remained largely unchanged for decades.

Functional analysis

The performance of the current socio-technical system around GPR was analysed using the seven system functions and is outlined in Table 2. A sufficient presence and smooth interaction among these functions should ideally have led to the successful development and diffusion of GPR within the SIS. However, we identified several systemic barriers impeding this progress. This section focuses on examining and explaining the structural-functional barriers and their interdependencies.

Entrepreneurial activities are predominantly confined to the supply side (SF1). The demand side exhibited a conservative, risk-averse culture that favours proven methods. One of the project managers interviewed elaborated on this: "We used GPR in the past, but it did not yield the desired results. Consequently, we reverted to our traditional methods." The reluctance to use GPR suggests a lack of legitimacy, driven by underwhelming experiences in prior applications. The broader issue, however, is the sector's limited learning through experimentation and developing knowledge on leveraging GPR's capabilities (SF2). This lack of experimentation was particularly evident among contractors. None of the contractors studied utilised GPR or explored its potential in their current surveying endeavours. There are also no specific subsidies or resource incentives for surveyors that could stimulate such experimentation (SF6).

Table 2: Summary of the performance per TIS function of the GPR case

#	System Functions	Function performance
SF1	Entrepreneurial Activities	Numerous GPR developers and service providers exist in the sector, but there is limited experimentation with GPR from the demand side. The sector generally exhibits risk aversion and favours proven methods.
SF2	Knowledge Development	Developing knowledge is primarily confined to the supply side and research institutes. This development emphasizes enhancing GPR services, prioritising user-friendly processing, and visualising outcomes.
SF3	Knowledge Diffusion	Collaborative efforts that facilitate knowledge dissemination from the supply to the demand side through 'learning by doing' with GPR are limited. Lessons on GPR use are generally not shared between users.
SF4	Guidance of the Search	Authorities mandate acquiring highly accurate utility information through national legislation and directives. Simultaneously, compliance standards implicitly favour proven surveying approaches.
SF5	Market Formation	There is little demand articulation for GPR. While the disadvantages of current technologies (mainly trial trenches) are widely shared, few clients have explicitly stimulated the development, improvement or use of GPR.
SF6	Resource Mobilisation	There are no specific subsidies on careful excavation or GPR, and few resource incentives exist for surveyors to replace trial trench practices.
SF7	Creation of Legitimacy	Advocacy for careful excavation methods is common during industry meetings, which typically focus more on excavation processes rather than geophysical detection methods like GPR.

Developing knowledge is primarily confined to the supply side and research institutes (SF2). New knowledge is developed to enhance GPR services, prioritising user-friendly processing and visualisation of outcomes. This developed knowledge, however, is only sparsely diffused to the demand side (SF3). Despite the presence of GPR user groups, such initiatives were limited. The insights from the project observations and interviews underscore the resulting knowledge gap regarding GPR. Quotes from project managers, such as "We never used GPR, and actually only know it by name" and "My knowledge of GPR is limited to what I have read and heard about it. I have never encountered it in the field," demonstrate this. This disparity in knowledge diffusion (SF3) impedes the necessary flow of knowledge from the supply and research side to the demand side.

Another barrier is evident within the guidance of the search function (SF4). National rules and directives revealed an implicit bias towards using trial trenches with utility maps. The national law mandates actors to notify excavation activities beforehand and study the exact location of utility networks at excavation sites. Although the law does not prescribe a specific excavation method, a directive guides the sector on surveying activities. This directive revealed a strong emphasis on trial trenching. Trial trenches are not only mentioned first but are also detailed through a six-stage

process. In contrast, GPR is merely mentioned as part of scanning technologies without specific guidance on its application. This directive has also been recognised as the compliance standard. In cases of utility strikes, Dutch courts use the directive to determine whether actors have conducted 'careful excavation.' Consequently, due to the directive's emphasis on trial trenching, trenches are sometimes mistakenly believed to be mandatory. In fact, during one of the industry meetings, nearly half of the respondents believed this to be true, hampering GPR's legitimacy (SF7).

Furthermore, clients and surveying contractors seemed hesitant to mobilise similar or even lesser resources for GPR compared to trial trenches (SF6). This reluctance was evident from statements made by project managers during interviews, such as "Less for GPR in case of replacement. Otherwise, a trial trench offers more certainty for the same or less money" and "Less than a trial trench, or the same if it offers more information." Due to trial trenching being superior to GPR in terms of accuracy and GPR's technical limitations, the idea of replacing trial trenches with GPR seemed not appealing to stakeholders. This issue stems directly from the demand side's lack of knowledge about GPR (SF2), as the technology offers more than just a replacement option. Moreover, economic incentives primarily drive market dynamics, with surveying projects often prioritising speed and cost efficiency. The absence of financial incentives for innovative surveying methods or careful excavation strengthens these dynamics (SF6). Collectively, these factors prevent the market from forming an innovative environment in which GPR is a viable option (SF5).

Building upon this, some contractors interviewed had previously used GPR but reverted to traditional methods due to GPR's failure to meet their information needs. GPR's practical uncertainties had led to instances of 'failed' applications, undermining its legitimacy as a surveying approach (SF7). This lack of legitimacy is further compounded by the challenge of interpreting GPR outcomes, which emerged as a recurring issue in the interviews and questionnaires. Additionally, there was limited advocacy for GPR during industry meetings. While there was a broad call for careful excavation across the Dutch utility sector, the agendas of these meetings revealed a priority on streamlining the overall excavation process. These meetings predominantly focused on information exchange rather than creating legitimacy for innovative surveying methods like GPR (SF7).

Systemic barriers to GPR adoption in the utility sector

Expanding on the structural-functional analysis, we identified three significant vicious cycles of interdependent systemic barriers sustaining a lack of GPR adoption within the Dutch utility sector: the knowledge cycle, the institutionalisation cycle, and the misalignment cycle. These cycles are visualised in Figure 2 and stick to the most apparent barriers contributing to them.

The knowledge cycle sustains the insufficient knowledge in practice regarding implementing and using GPR (SF2). Insufficient knowledge regarding the capabilities and limitations of GPR within the surveying practice persists as the Dutch utility sector exhibits limited learning through experimenting with GPR (SF1). The demand side is conservative and risk-averse, and little collaborative effort is observed between the demand and supply sides. This results in limited knowledge diffusion between the two (SF3). This lack of knowledge undermines the legitimacy of GPR as a surveying approach (SF7) and diminishes the sector's entrepreneurial activities and experimentation with GPR (SF1), sustaining the observed knowledge barrier.

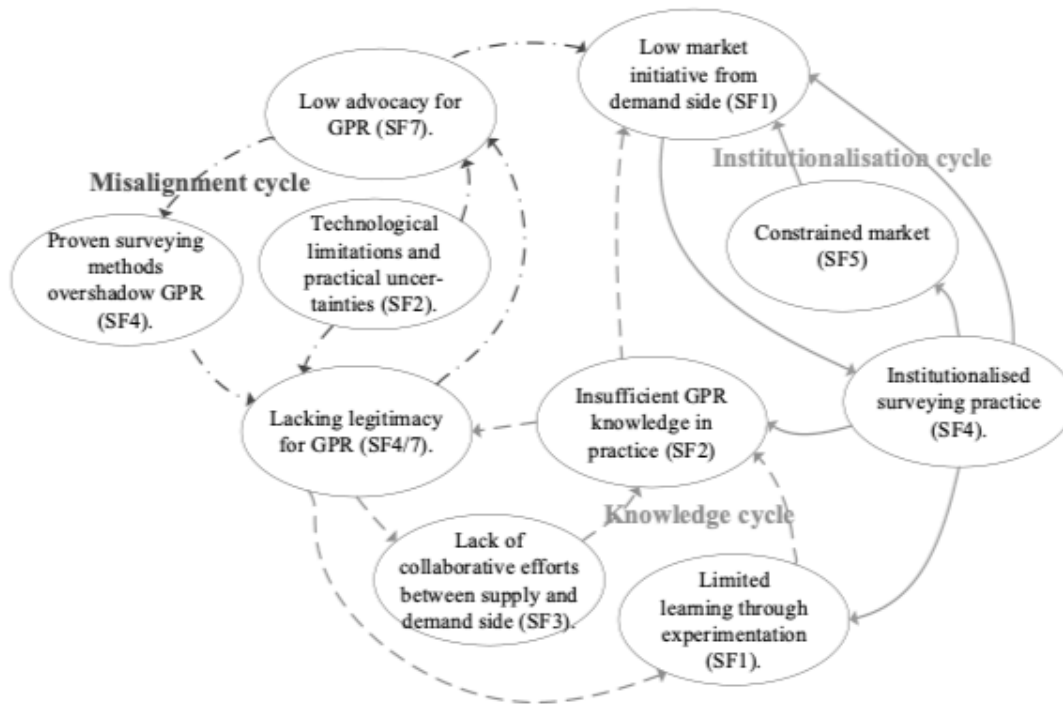


Figure 2: Three cycles of systemic lock-ins to the adoption of GPR in the Dutch utility sector

The institutionalisation cycle sustains the institutionalised surveying practice that excludes GPR. The institutionalised surveying practice steers the demand side away from experimenting with GPR (SF1) and developing knowledge about its use (SF2), favouring proven methods instead. Furthermore, economic incentives thrive within project-based surveying activities, prioritising short-term economic gains over safety and comprehensive surveying practices. This hinders resource mobilisation and discourages investment in GPR as an innovative surveying method. These constraints prevent the market from developing supportive niches for adopting GPR (SF5), allowing the surveying practice to sustain as-is.

The misalignment cycle sustains the lack of legitimacy for GPR (SF7). On one hand, there is an urgency to reduce excavation damages and increase productivity; on the other hand, little legitimacy is being created for GPR technology, even though it can contribute to these goals. Proven surveying methods overshadow GPR (SF4) due to low advocacy for GPR in the sector (SF7). Also, technological limitations and practical uncertainties associated with implementing GPR steer the demand side away from considering GPR as a viable option for their surveying efforts. Without widespread recognition and endorsement within regulatory frameworks and professional communities, GPR struggles to gain traction as a viable alternative to trial trenches, thereby sustaining the cycle of lacking legitimacy.

The three cycles 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 organisations from experimenting with the technology and developing knowledge about its use. Simultaneously, the absence of knowledge and legitimacy sustains institutionalised surveying practices and the lack of market initiative from the demand side, altogether hindering the adoption of GPR.

CONCLUSIONS

In exploring why GPR technology has not become a common alternative to trial trenches, three self-reinforcing cycles were identified - the knowledge cycle, the institutionalisation cycle, and the misalignment cycle. These cycles reveal that the limited adoption of GPR is driven more by institutionalised surveying practices excluding GPR, a lack of legitimacy, and insufficient knowledge development and diffusion than by the technological limitations of GPR itself.

In particular, the knowledge cycle highlights how limited understanding and awareness of GPR's capabilities and limitations hinder its adoption. Stakeholders may be reluctant to invest in unfamiliar technologies without a clear understanding of their capabilities and limitations. The institutionalisation cycle underscores how entrenched institutional practices favour traditional methods over the newer GPR technology. This institutional inertia sustains the status quo and stifles innovation in surveying practices. The misalignment cycle reveals the broader societal and institutional factors that contribute to the sustaining lack of legitimacy for GPR. Consequently, GPR struggles to gain traction as a viable alternative to trial trenches.

These findings emphasize the need to address systemic barriers to the adoption of technologies like GPR by integrating them into social and institutional contexts rather than focusing solely on their technological capabilities. For construction management scholars, this article demonstrates the efficacy of using TISs as an analytical framework to identify such barriers for technologies struggling to find adoption. Our findings challenge the traditional emphasis on technological excellence and advocate for the establishment of supportive institutional environments that can legitimise and facilitate the adoption of innovative solutions. Especially since workloads increase while labour availability decreases, enabling the successful adoption of (digital) technologies that enhance productivity becomes more crucial than ever.

To practice, this study provides a foundation for developing comprehensive strategies to address the systemic barriers hindering GPR adoption in the utility sector. GPR presents a pivotal opportunity to enhance operational efficiency and mitigate risks associated with traditional surveying methods. To facilitate its adoption, we 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, as well as implementing and evaluating pilot projects that demonstrate the effectiveness and capabilities of GPR in utility surveying. Furthermore, we emphasize the importance of fostering a supportive regulatory environment for GPR adoption. Initiatives could begin by positioning GPR as a viable option within directives on surveying.

While our findings may not entirely generalise to other contexts and SISs, we believe our core systemic lock-in, characterised by a lack of legitimacy, knowledge, and institutionalised surveying procedures, represents systemic barriers that may also be prevalent beyond the Netherlands. Therefore, our findings could serve as a common reference point for other studies and inform general strategies for policy interventions aimed at accelerating the adoption of GPR. However, we recommend that future research first delve deeper into the micro-dynamics of the studied sector to uncover nuances that broad analyses (i.e., at the sector level) might overlook, thereby enhancing our understanding of these systemic barriers.

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